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Devising quality assurance procedures for assessment of legacy geochronological data relating to deglaciation of the last British-Irish Ice Sheet

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A B S T R A C T

This contribution documents the process of assessing the quality of data within a compilation of legacy geochronological data relating to the last British-Irish Ice Sheet, a task undertaken as part of a larger community-based project (BRITICE-CHRONO) that aims to improve understanding of the ice sheet's deglacial evolution. As accurate reconstructions depend on the quality of the available data, some form of assessment is needed of the reliability and suitability of each given age(s) in our dataset. We outline the background considerations that informed the quality assurance procedures devised given our specific research question. We describe criteria that have been used to make an objective assessment of the likelihood that an age is influenced by the technique specific sources of geological uncertainty. When these criteria were applied to an existing database of all geochronological data relating to the last British-Irish Ice Sheet they resulted in a significant reduction in data considered suitable for synthesis. The assessed data set was used to test a Bayesian approach to age modelling ice stream retreat and we outline our procedure that allows us to minimise the influence of potentially erroneous data and maximise the accuracy of the resultant age models.

Contents

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1. Introduction

Numerical ice sheet models provide insights into the response of ice sheets around the globe to various global warming scenarios, but these models have to be validated through comparison with field evidence relating to the evolution of former ice sheets (Stokes et al., 2015). The accurate reconstruction of rates and patterns of deglaciation is, in turn, fundamentally dependent on the quality of the geochronological data that provides a temporal framework. As early as the 1950s advances in radiocarbon (^{14}C) dating permitted glacial events to be constrained in absolute time (e.g. Flint, 1955; Godwin and Willis, 1959). In the subsequent decades, palaeo ice sheets around the world became better constrained by steadily rising numbers of absolute geochronometric ages, firstly by ^{14}C and then by luminescence (e.g. Berger and Eyles, 1994; Duller et al., 1995) and cosmogenic dating (e.g. Phillips et al., 1990, 1994). When age measurements were scarce glaciological reconstructions of entire sectors often hinged on a small number or even individual ages. A classic example for the British-Irish Ice Sheet (BIIS) were the Dimlington ages for maximum ice advance in East England (Penny et al., 1969). As more ages became available it became apparent that ice sheets did not reach their maximum extents or retreat synchronously. Subsequently, ice sheets became a focus for investigation to improve understanding of global climatic teleconnections (e.g. Denton and Hendy, 1994; Gosse et al., 1995; Osborn et al., 1995; Ivy-Ochs et al., 1999, Barrows et al., 2007; Moreno et al., 2009)

The ever-increasing accumulation of legacy geochronological data is spread across hundreds of different publications, making it difficult to address regional or ice sheet scale reconstruction; this can be termed the Compilation Problem. It has recently been addressed for many ice sheets including the Laurentide Ice Sheet (Dyke et al., 2002), the British-Irish Ice Sheet (Hughes et al., 2011), the Antarctic Ice Sheets (Bentley et al., 2014) and the Eurasian Ice Sheets (Stroeven et al., 2015; Hughes et al., 2016). These geochronological compilations reveal how numerous age constraints have become. However, they can also reveal incompatibility or direct conflicts between ages. Such conflicts are not surprising for two reasons. Firstly, dating techniques and their robustness have vastly improved over time (Lowe and Walker, 2015). Secondly, the geological context of the material sampled for dating might have more than one interpretation, or the strength of the association between an age and the event that is of interest may vary. Both factors yield conflicts in specific regions that have often forced authors of a reconstruction to rely on some ages but argue against others. It is apparent that not all legacy ages are equally-robust with respect to addressing a specific research question; this can be termed the Quality Problem.

The issue of quality assurance of geochronological data has received considerable attention in various areas of science including the archaeological (e.g. Pettitt et al., 2003; Blockley et al., 2008; Graf, 2009) and paleoclimatological (e.g. Lowe and Walker, 2000; Brauer et al., 2014) communities with the radiocarbon technique specifically receiving much attention. These studies have highlighted a range of issues that can influence the quality of geochronological data and many have gone on to define set criteria for assessing the reliability of data (e.g. Pettitt et al., 2003; Graf, 2009; Blockley and Pinhasi, 2011). Within archaeology and paleoclimatology much of the focus has been on assessing data that exists in very close association with other data (e.g. ^{14}C dates from a sequence) and more rarely with sparsely distributed data. Additionally, the resolution that is sought is often on the order of 10^1–10^2 years. For the reconstruction of past ice sheets this concentration of data from a single location and achievable resolution is desirable but also generally rare. While some glaciological compilations have been provided with internal quality assurance, the DATED project (Hughes et al., 2016) being a recent and commendable example, little has yet been published in the ice-sheet literature about the underpinning decision making criteria and pragmatic approaches to the task.

A large consortium of researchers (>45) are currently working on the BRITICE-CHRONO project to better constrain the retreat history of the BIIS (Clark, 2014), acquiring new ages and appraising the existing legacy data (Hughes et al., 2011). In order to inform ice sheet reconstructions, and to feed into future numerical modelling, a systematic approach to how all ages are to be used has been devised to address the 'Quality Problem'. It is the purpose of this paper to outline the guidelines used to assess a legacy data set and the criteria devised for doing so. A review is provided of the issues that can introduce geological uncertainty into dating deglaciation by the most commonly applied techniques. We outline how consideration of these was used to create technique-specific guidelines and criteria for assessing geochronological data for constraining rates and patterns of deglaciation. We integrated the assessed data with Bayesian age modelling and outline a procedure for maximising the confidence that can be achieved in the results.

2. Dating deglaciation

Observations of current ice margins (e.g. in Antarctica) can robustly and directly constrain the timing of ice advance and retreat on annual timescales (Rignot et al., 2014), but such observations are limited to the last few decades over which we have aerial photographs and satellite images. The need to understand the longer-term significance of observed changes in modern ice sheets demands a means to reconstruct changes in ice sheets over timescales relevant to deglaciation; i.e. 10^2–10^5 years (Stokes et al., 2015). However, beyond the limits of direct observations there is no geochronological technique that can directly constrain the timing of glacial advance or retreat, rather we date features within the geomorphological and sedimentary record (Fig. 1) that are formed before, during or after deglaciation, and can thus be directly (e.g. an exposed glacial surface) or indirectly (e.g. fluvioglacial outwash) linked to past ice extents. Geochronological control on such features can represent minimum or maximum ages for deglaciation depending on the geomorphic and/or stratigraphic context of the sample collected and the quality of the ages fundamentally influences subsequent interpretation (Fig. 2).

Within any compilation of geochronological data an unknown proportion of measured samples will be affected by factors that can make the resulting ages inaccurate. Ages obtained from chronological methods are derived from the measurement of specific physical properties (e.g. the ratio of $^{10}Be/^{9}Be$ in cosmogenic nuclide dating). The actual measurement of a physical property has a set of defined systematic and random uncertainties associated with processing and measurement which are reflected in the quoted error term that accompanies the reported result. The measured physical property(s) are used to calculate an equivalent calendar age that is then assumed to be contemporaneous with, or constrain, the age of the event of interest. Wrapped up within these assumptions of equivalence are other sources of uncertainty

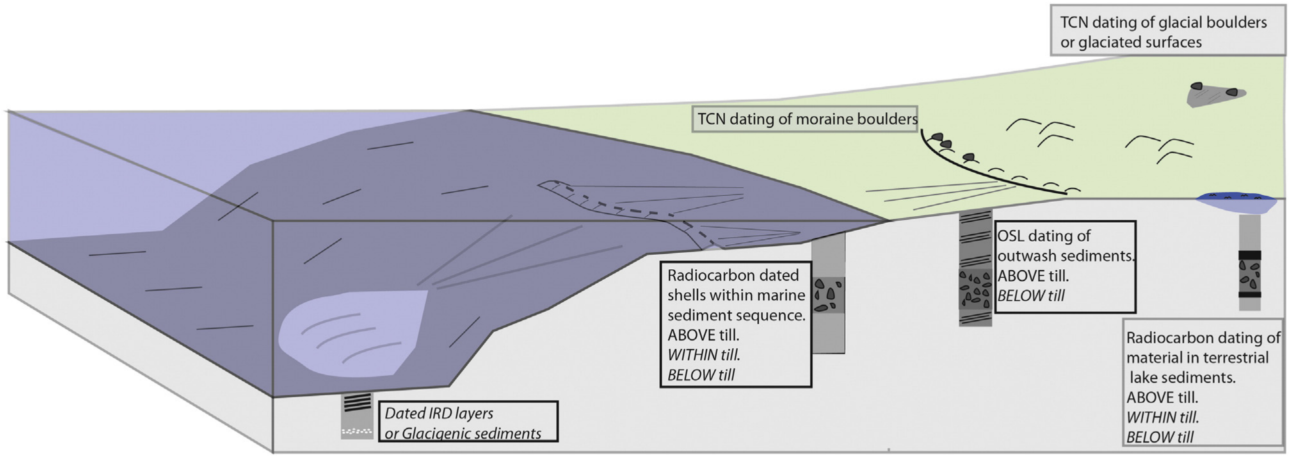

Fig. 1. Simple schematic of a deglaciated landscape depicting some of the key geomorphic and stratigraphic scenarios where ages approximating deglaciation can be obtained using one of the three main geochronological techniques (TCN, ^{14}C, and OSL). Additional constraints can be obtained from particular marine sediments such as IRD layers and glacigenic sediments. Normal text depicts minimum deglaciation ages, italics depict maximum deglaciation ages.

which can be broadly separated into two categories; factors that could have affected the measured property before sampling and over which workers have limited control, and the strength of the geological association between the material that is being dated and the event of interest. While recognizing that there is a wide range of potential sources of uncertainty that fall under these two categories we use the broad term 'geological uncertainty' to describe both. We consider this appropriate as in both categories it is the geological history or context of the sampled material that is the source of the uncertainty. As it is not possible to quantitatively constrain all sources of geological uncertainty there is no guarantee that an age derived from a measurement will be an accurate and/or precise constraint on a geological event. Every geochronological technique measures different material in different settings and as such they implicitly suffer from different sources of geological uncertainty.

Numerous geochronological techniques have been utilised to investigate past ice extent and other related questions. However, the vast majority of available ages are contributed by three techniques namely; cosmogenic exposure dating, luminescence dating and ^{14}C dating. As such we focus further discussion on these methods. Other techniques, such as tephrochronology have high potential for providing age constraints on sediments associated with glacial retreat however, as yet it has seen relatively little systematic application in constraining ice sheet deglaciation (cf. Kirkbride and Dugmore, 2006, 2008) and there are no tephrochronology data within the BRITICE v1 database. Lowe (2011) provides a detailed review of tephrochronology and the interested reader is directed there.

2.1. Cosmogenic nuclide exposure ages

(Terrestrial) cosmogenic nuclides (CN) are produced by interactions between minerals exposed at the Earth's surface and secondary cosmic radiation. A variety of isotopes are produced by these interactions including radioactive ^{10}Be, ^{26}Al, ^{36}Cl, ^{14}C and the stable noble gas isotopes ^{21}Ne and ^{3}He. The differing properties of the various CN (i.e. differing half-lives and production rates) result in them being used to address a range of geochronological and geomorphological questions while their various production mechanisms allow them to be applied to a wide variety of lithologies. Of the CN available to researchers ^{10}Be, ^{26}Al and, ^{36}Cl are, by some distance, the most widely applied to constraining the past extent and deglaciation of ice sheets (e.g. Stone et al., 2003; Bentley et al., 2006; Briner et al., 2003; Ballantyne et al., 2009a; Svendsen et al., 2015).

^{10}Be and ^{26}Al are produced within quartz through spallation (of O and Si respectively) and muon capture (Gosse and Phillips, 2001). The primary production pathways of ^{36}Cl are spallation of K and Ca, muon capture by K and Ca and, thermal neutron capture by ^{35}Cl (Zreda et al., 1991; Schimmelpfennig et al., 2009). The differing production pathways of ^{36}Cl mean it can be applied to rocks that are quartz poor, including carbonates and mafic igneous rocks (e.g. basalts). Due to the differing properties of the particles involved the relative importance of the production pathways changes with depth beneath the Earth's surface. Most CN studies use ^{10}Be to determine exposure ages as ^{26}Al measurements have larger measurement uncertainties (Gosse and Phillips, 2001) (n.b. ^{26}Al is most commonly applied alongside ^{10}Be as a test for complex exposure histories). The relatively ubiquitous occurrence of quartz within crustal rocks results in ^{10}Be being the CN most widely applied to constraining ice sheet extent.

CN exposure dating has been widely applied to the majority of extant and former ice sheets (including the BIIS) and has made a significant contribution to our understanding of their past extents and evolution through time (cf. Balco, 2011). The focused production of CN within the top few metres of the Earth's surface makes them particularly useful for exposure dating features related to past ice sheets such as moraine boulders (e.g. Small et al., 2012), glacially transported boulders (e.g. Fabel et al., 2012) and, glacially modified bedrock (e.g. Stone and Ballantyne, 2006). When an ice margin retreats and first exposes the material CN production begins. The CN concentration within samples taken from these surfaces can then be used to calculate an exposure age which, if all assumptions hold, will closely equate to the time of deglaciation.

2.1.1. Obtaining a CN exposure age

Analysis for CN exposure dating is undertaken by accelerator mass spectrometry (AMS) which measures a ratio (e.g. ^{10}Be/^{9}Be) for the isotope of interest and this ratio is then used to calculate the concentration of the CN, reported in atoms per gram. Knowledge of the CN concentration allows calculation of an exposure age when combined with knowledge of the production rate. Numerous studies have attempted to establish production rates for the various nuclides (Nishiizumi et al., 1989, 1996; Masarik and Reedy, 1995; Swanson and Caffee, 2001; Schimmelpfennig et al., 2009) and improving constraints on production rates is an ongoing field of research (e.g. Small and Fabel, 2015; Marrero et al., 2016a). Currently there are two online calculators that can calculate exposure ages from the calculated CN concentration and relevant sample data (e.g. latitude, longitude, elevation, sample thickness, sample density, topographic shielding correction factor, AMS standard). The most widely used of these is the CRONUS-Earth online calculator (Balco et al., 2008; http://hess.ess.washington.edu). Users have the option of calculating ^{10}Be exposure ages using a globally calibrated

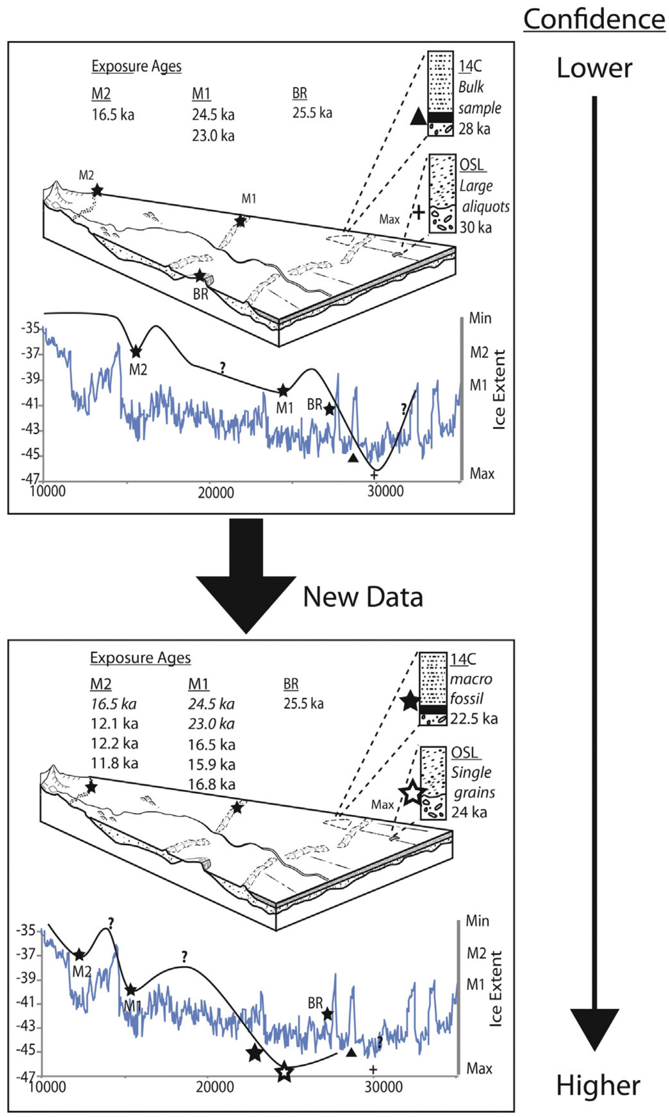

Fig. 2. A hypothetical deglaciation sequence initially populated with ages that are taken at face value to reconstruct changes in ice extent in a palaeoclimatic context using the NGRIP $\delta^{18}O$ record (Rasmussen et al., 2006). Addition of new data fundamentally changes the interpretation of the relationship between changes in ice extent and climate. In this hypothetical example the large aliquot OSL age is several ka older than the age obtained using the single grain approach (e.g. Duller, 2006, 2008). The bulk radiocarbon age is older than the radiocarbon age obtained from a macrofossil in the same horizon (e.g. Grimm et al., 2009). The TCN ages in the original scenario reflect nuclide inheritance which is only identifiable if sufficient samples exist (e.g. Everest et al., 2013). While this example is deliberately extreme it is intended to highlight that the availability of data exerts a fundamental control on the subsequent reconstruction.

production rate or a local production rate (e.g. Balco et al., 2009; Putnam et al., 2010; Young et al., 2013; Small and Fabel, 2015). The other online calculator (CRONUScalc; Marrero et al., 2016b; http://web1.ittc.ku.edu:8888/2.0/html) includes functionality for calculating exposure ages with nuclides other than ^{10}Be and ^{26}Al. It also includes the option to scale production rates using the newly available Lifton-Sato-Dunai scaling scheme (Lifton et al., 2014). It currently does not include online functionality to calculate exposure ages using a user defined production rate.

The various options available for calculating exposure ages in terms of choice of production rate, scaling factors and now, calculation method are likely to result in a variety of approaches being taken in the literature. For data compilations for use in ice sheet reconstructions it is vital that there are sufficient supporting data describing the analytical procedures, primary data collected and, calculation methods. This allows published ages to be recalculated so that all CN ages and their uncertainties are comparable within a given geochronological compilation. For our purposes we recalculated ^{10}Be exposure ages using the CRONUS-Earth calculator (Balco et al., 2008) using the Lm scaling scheme and erosion rates as specified by the original authors for all samples. We use a local production rate derived from Fabel et al. (2012).

CN exposure ages are reported in years before present (a or ka). Ages are generally reported with two uncertainty values (both at $\pm 1\sigma$); the internal uncertainty reflecting the uncertainty on the measured AMS ratio and the external uncertainty which includes systematic uncertainties including production rate uncertainties and uncertainties introduced by sample processing (Dunai, 2010). The internal uncertainty is commonly used to assess consistency between ages obtained from a single location and processed together through the same lab, where systematic uncertainties can be taken as being equal for all ages. External uncertainties are used for comparison to exposure ages from other locations and for comparison to other dating techniques.

2.1.2. Sources of geological uncertainty

Assumptions made regarding the exposure and shielding history of any given sample have the potential to introduce significant geological uncertainty to any given exposure age. For the purposes of constraining ice sheet retreat these assumptions are that there has been no prior exposure of a surface to cosmic radiation (inheritance; Fig. 3) and that since deglaciation exposure has been continuous and constant (partial exposure) (Balco, 2011). Sampling for cosmogenic exposure dating requires careful selection of samples to minimise such complicating issues. Studies that address first order questions, such as whether an area was ice free during the Last Glacial Maximum (LGM), are relatively insensitive to geological uncertainty (e.g. Ballantyne, 2010). In contrast, high-resolution reconstructions of rates and patterns of deglaciation require geochronological data that reflect the true age of deglaciation as accurately as possible, thus all sources of geological uncertainty potentially become significant. Inheritance occurs where there is insufficient removal of material to completely remove any existing accumulation of CN. In glacial landscapes it is most commonly encountered when sampling landforms formed predominantly by glacial abrasion (e.g. Briner and Swanson, 1998), where sub-glacial erosion rates can be relatively low (Hallet, 1979). It is less common when sampling landforms formed by glacial plucking (Colgan et al., 2002) and rare when sampling glacially transported boulders of sub-glacial origin (Fig. 4) (Putkonen and Swanson, 2003; Heyman et al., 2011), given the higher rates of erosion associated with these processes (Hallet et al., 1996). While there has been a general focus on boulders (Balco, 2011), many studies have sampled other glacial landforms, and any compilation is likely to feature a range of sample settings where inheritance is possible and thus its likelihood must be assessed.

'Partial exposure' describes a wide range of processes that can act to reduce the rate of CN accumulation following landform exposure or, in the case of erosion, remove material containing a proportion of the accumulated CN inventory. To reduce the rate of CN accumulation requires the sampled material to have been shielded by a material, attenuating the incoming cosmic radiation with a concomitant reduction in the production rate. Water, snow, soil, and vegetation can all attenuate cosmic radiation and, if cover is sufficiently thick, attenuation can be total (Gosse and Phillips, 2001). Erosion of an exposed surface removes material containing a proportion of the accumulated CN and reveals material that was previously shielded. This newly exposed material was accumulating CN at a lower rate than the removed material because of the attenuation of cosmic rays with depth, and thus has a CN inventory lower than expected if there had been no erosion. Consequently, if no account is taken of erosion, sampling this material will result in an underestimation of the true exposure age. In general rates of erosion on crystalline rocks in glacial environments are quite low at c. 2 mm ka^{-1} (André, 2002), but other more friable lithologies, sporadic

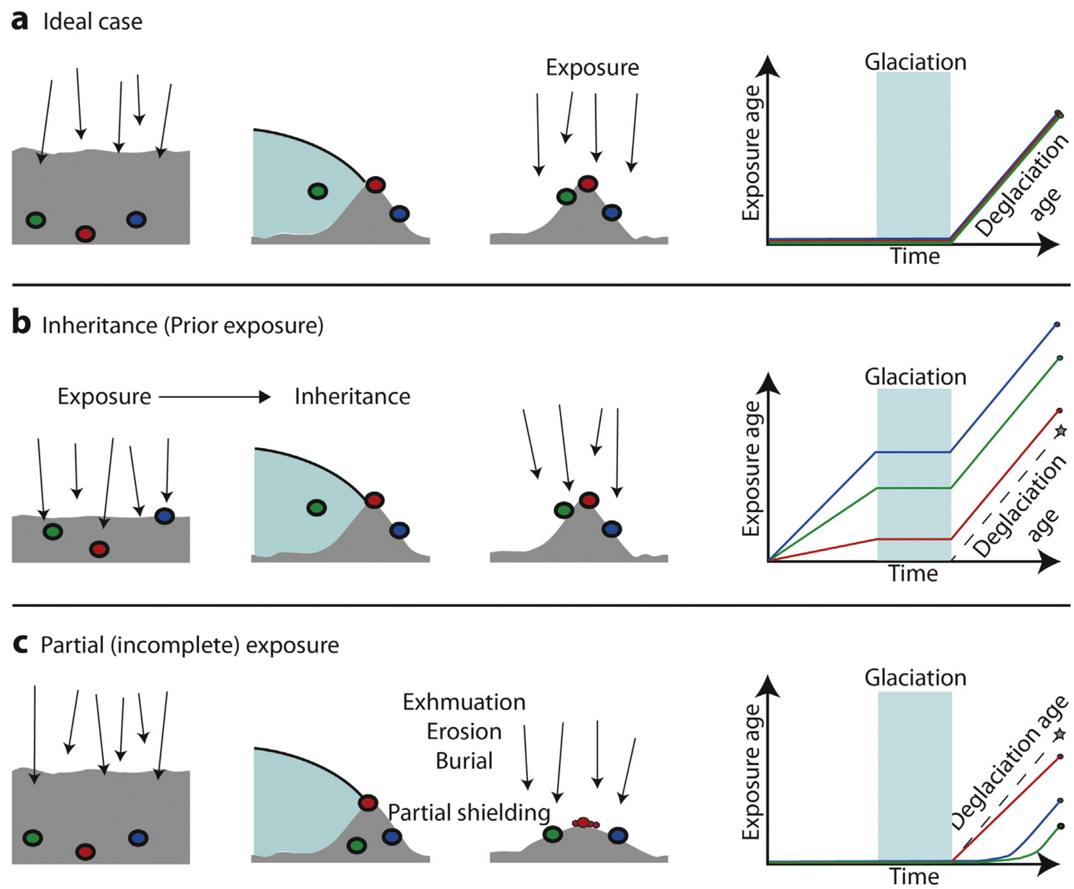

Fig. 3. Potential scenarios to be considered when using TCN dating from Heyman et al. (2011). a) The sample has been completely shielded from cosmic rays prior to glaciation and continuously exposed since deglaciation. b) Sample is exposed to cosmic rays prior to glaciation and experiences no post-glacial shielding (prior exposure) the apparent exposure age will exceed the deglaciation age. c) Sample is completely shielded from cosmic rays prior to glaciation and partially shielded from cosmic rays following deglaciation (incomplete exposure) the apparent exposure age will be younger than the deglaciation age.

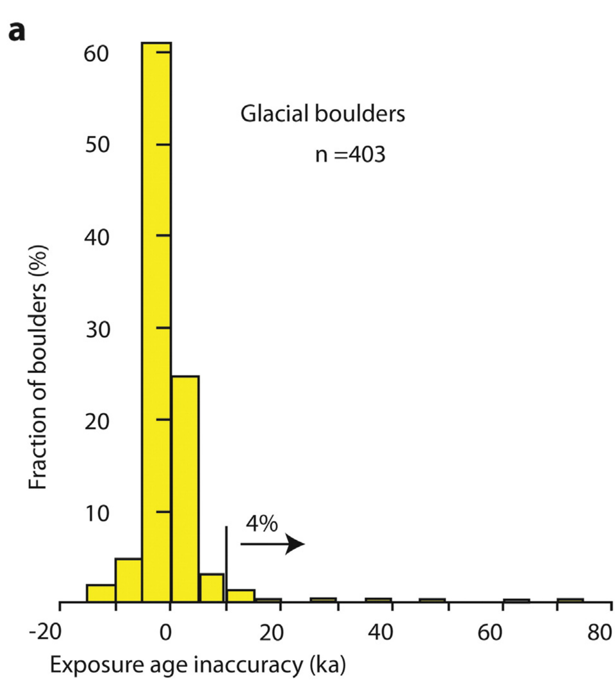

Fig. 4. Histogram of exposure age inaccuracies from compilation of published exposure ages (Heyman et al., 2011). Positive numbers are ages older than expected (inheritance), negative numbers are ages younger than expected (partial exposure).

episodes of exfoliation (Zimmerman et al., 1994) and granular disintegration (Kirkbride and Bell, 2010) can lead to higher erosion rates.

As there is no way of quantitatively assessing the potential for inheritance and/or partial exposure in a single exposure age, workers generally focus on obtaining multiple ages from the same feature (Putkonen and Swanson, 2003; Balco, 2011). This allows the use of various approaches to identify and exclude outliers that can reasonably be argued on statistical (e.g. Chauvenet's criterion) and/or geomorphic grounds to have been affected by geological uncertainty. Ages that cannot be excluded, particularly if they cluster tightly, can then be judged as representative of the true exposure age of the sampled landform. Balco (2011) provides a useful review of the differing approaches used to assess datasets for the effects of geological uncertainty the most commonly applied being the reduced chi-squared statistic x_R^2 which is given by;

$$x_R^2 = (n-1)^{-1}\Sigma\left[\left(t_i - t_{avg}\right)^2/{\sigma_i}^2\right]$$

Where $t_1 \ldots t_n$ are a set of apparent exposure ages, $\sigma_{1\ldots}\sigma_n$ are the corresponding measurement (internal) uncertainties and t_{avg} is the arithmetic average of the apparent exposure ages. This statistic compares the observed scatter within a dataset to the scatter expected from measurement uncertainty alone. For a dataset with infinite degrees of freedom, $x_R^2 \approx 1$ if measurement uncertainty is the sole cause of the observed scatter (Bevington and Robinson, 2003); but for more restricted datasets with fewer degrees of freedom (such as geochronological data) higher x_R^2 values are associated with acceptable p-values (Bevington and Robinson, 2003; their Table - C4). If the x_R^2 is higher than the appropriate threshold then it is inferred that geological uncertainty is contributing to the observed scatter. The age of a given landform is usually defined by the ages that cluster together and generally taken as the arithmetic mean. Error-weighted means are dominated by ages with lower AMS uncertainties. As there is no reason to assume such ages are more accurate with respect to dating an event of interest use of error-weighted means is not favoured (Brauer et al., 2014).

2.2. Radiocarbon

^{14}C is produced in the upper atmosphere through the interaction of ^{14}N and cosmic radiation. ^{14}C readily binds with O to produce CO_2 after which it mixes through the atmosphere, is absorbed into the ocean and, through photosynthesis and the food chain, becomes fixed in living organisms. Unlike the other carbon isotopes (^{12}C and ^{13}C) ^{14}C is radioactive thus following death the concentration of ^{14}C (and the ratio of radioactive/stable isotopes) within an organism decreases at a known rate. Using these characteristics a measurement of ^{14}C from a deceased organism can be used to calculate the time since death (Libby et al., 1949; Arnold and Libby, 1951). This ability to date organic material has been extensively applied in a wide variety of fields where geochronological data that constrains the age of an object (e.g. archaeology) or a deposit (e.g. archaeology, paleoenvironmental [including glacial] studies) is vital.

Within paleoenvironmental studies radiocarbon has been widely applied to date sedimentary archives containing proxy records that can be related to past climate change (e.g. Lowe et al., 2004; Wohlfarth et al., 2006; van Asch et al., 2012). In this context samples are taken from various depths within a sequence and ages from these used to constrain the timing of observed changes in paleoenvironmental proxies (e.g. air temperature reconstructions, $\delta^{18}O$ records). ^{14}C ages may also be used to assist with 'wiggle-matching' to a regional stratotype such as the Greenland ice core records (e.g. Small et al., 2013). Radiocarbon has also provided valuable constraints on the past evolution of ice sheets (e.g. Dyke et al., 2002; Ó'Cofaigh and Evans, 2007; Lowell et al., 2009). This is despite the obvious limitation that glaciers and ice sheets do not directly deposit organic material, thus any organics found in association with glacial deposits must have lived some time before or after the glacial event.

Radiocarbon can be used to constrain past ice sheet evolution in a variety of ways. Ice advance can be constrained by dating organic material reworked into glacial deposits (Ó'Cofaigh and Evans, 2007) with such ages providing a maximum age for ice advance. Constraining deglaciation using radiocarbon is most commonly achieved by dating basal organics with close association to glacial deposits (e.g. Dyke, 2004; Lowell et al., 2009). These ages provide a minimum age of deglaciation. Similarly almost any ^{14}C age can be interpreted as a minimum deglaciation age if it is not stratigraphically overlain by glacial deposits. In this way basal ages from sedimentary sequences sampled for other paleoenvironmental studies can be included in geochronological compilations for use in constraining glaciation even if there is not a close association with glacial deposits.

2.2.1. Obtaining a ^{14}C age

To obtain a ^{14}C age a sample of organic material is taken from the horizon of interest. Radiocarbon analyses are undertaken on a variety of material including bulk organic sediments, wood, charcoal, bone, seeds, leaves and, marine macro- and micro-fossils. The sample may be collected in the field but is more commonly extracted from processed samples (e.g. monoliths or cores) in a laboratory. The wide variety of material suitable for radiocarbon dating requires careful sample selection, where such a choice exists, as the differing life environments of organisms can result in them producing variable ^{14}C ages (cf. Lowe et al., 2001; Walker et al., 2001). Following sampling material can be subject to various pre-treatments, which can influence the accuracy of the ^{14}C age (e.g. Bird et al., 1999; Jacobi and Higham, 2008; Blockley et al., 2008). It is then prepared for analysis either through traditional beta-counting techniques (based on decay of ^{14}C) or through AMS measurement of carbon isotope ratios. Radiocarbon dating carried out through beta-counting can produce ages of comparable accuracy to AMS (Walker et al., 2001; Boaretto et al., 2002) thus there is no intrinsic reason to favour ages produced by one technique over the other. AMS does however allow for measurement of ^{14}C in considerably smaller samples. Thus, while traditional beta-counting techniques requires several grams of carbon, AMS analyses can be undertaken on mg of material. Results are reported as conventional radiocarbon ages (^{14}C yrs BP [before 1950]) which include a $\delta^{13}C$ correction for isotopic fractionation (Stuiver and Polach, 1977). Ages are reported at $\pm 1\sigma$ with uncertainties reflecting counting statistics and corrections.

Due to changes in the atmospheric $^{14}C/^{12}C$ ratio over time (Stuiver and Suess, 1966) and, by convention, the use of the original 'Libby' half-life value (Stuiver and Polach, 1977) ^{14}C ages (^{14}C yrs BP) do not equate to calendar years and require calibration. Radiocarbon calibration curves are constructed by comparing raw ^{14}C data to independently acquired calendar ages, ideally an absolute record that has directly incorporated carbon from the atmosphere at time of formation (Reimer et al., 2013). Tree rings are optimal records for radiocarbon calibrations as they can be independently dated through dendrochronology and the tree ring based calibration curve now extends to 13.9 ka (Reimer et al., 2013). The incorporation of other records (e.g. speleothems, varved records) has resulted in the most recent calibration curve (INTCAL13) extending over the last 50 ka (Reimer et al., 2013). Calibration curves have been extended and refined over time resulting in a variety of different calibration curves being applied to ^{14}C ages in the literature (e.g. Stuiver and Reimer, 1986, 1993; Reimer et al., 2004, 2009, 2013; Fairbanks et al., 2005). Data calibrated using one curve is not, sensu stricto, directly comparable to data calibrated using another and differences in the resulting calibrated ages (cal a BP) have the potential to hinder comparison of published geochronological information.

A variety of software exists for the calibration of radiocarbon data including OxCal (Bronk Ramsey, 2013; http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html) and CALIB (Stuiver and Reimer, 1993; http://www.calib.org). Calibration of conventional ^{14}C ages results in an output of possible corresponding calendar ages. The variations in the $^{14}C/^{12}C$ ratio over time manifest as 'wiggles' in the calibration curves that can cause some ^{14}C measurements to have multiple possible calibrated ages (Fig. 5). With a carefully constructed sampling strategy comprising several closely spaced samples those wiggles can be used to improve the certainty of the calibration (Lowe and Walker, 2000) however, most legacy data has insufficient sampling density to utilise the wiggles constructively.

2.2.2. Sources of geological uncertainty

Lowe and Walker (2000) identify three sources of error in ^{14}C ages; 1) Calibration to calendar years, 2) Laboratory contamination (and measurement precision) and 3) Site specific geological problems. Calibration uncertainties are controlled by the accuracy of the applied calibration curve and are intrinsic with the radiocarbon method. By standardising the calibration applied within a geochronological compilation these uncertainties are consistent within a data-set and, by declaring raw measurements and uncertainties within the compilation, calibrations can be updated. Data compilers (and users) are clearly unable to influence uncertainties introduced by laboratory contamination and/or procedures. The radiocarbon community has undertaken an extensive program of quality assurance to give confidence in the comparability between results and amongst laboratories (e.g. Long and Kalin, 1990; Scott et al., 2010). While some older results may not have been subject to such rigorous procedures it is impractical to attempt an ad hoc assessment of comparability between results within a geochronological compilation. Given this it is most practical to treat all ^{14}C ages within a geochronological compilation as being comparable.

'Site specific geological problems' are the most relevant for undertaking quality assurance on legacy data. This category comprises two

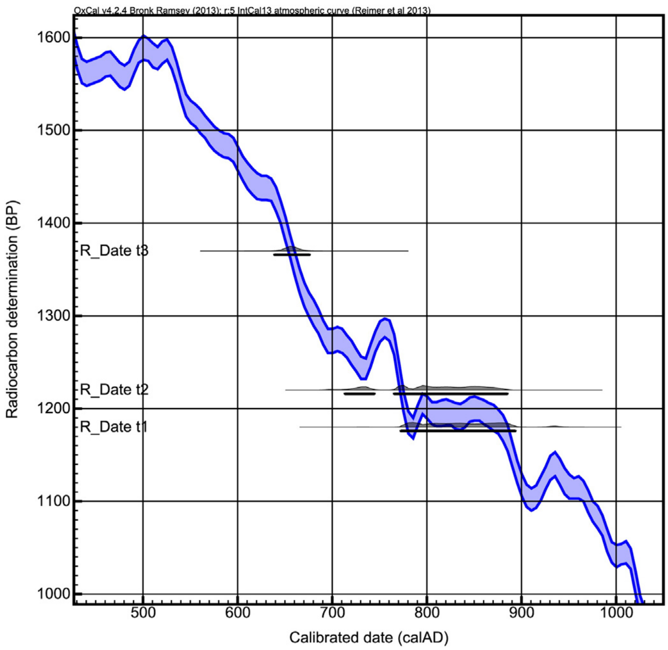

Fig. 5. INTCAL13 calibration curve (Reimer et al., 2013) from c.500–1000 calAD showing three radiocarbon calibrations. R_Date t1 falls on a radiocarbon plateau giving a wider range of probability and thus increasing the geological uncertainty introduced by calibration. R_Date t2 encompasses a radiocarbon reversal which yields two distinct age probability distributions. R_Date t3 falls on a tightly defined part of the calibration curve, minimising the geological uncertainty introduced by calibration.

main sources of uncertainty; i) processes, other than radioactive decay, that influence the $^{14}C/^{12}C$ ratio in the organism (before or after death), and ii) processes that result in the age of the sample not accurately reflecting of the age of the adjacent sediments. Consideration (i) relates to chemical processes that include isotopic fractionation, recrystallization, contamination and reservoir effects. Consideration (ii) relates to the physical processes through which the sampled material was transported and deposited which give rise to its geological context with respect to an event of interest.

Several chemical processes are important considerations for obtaining accurate ^{14}C ages. Isotopic fractionation occurs naturally due to the preferential uptake of light isotopes (i.e.^{12}C, ^{13}C) over heavier isotopes (i.e. ^{14}C) in some biochemical processes (Craig, 1953). It can be corrected for by measuring $^{13}C/^{12}C$ in the sample and normalising to an agreed value (Stuiver and Polach, 1977). This produces a standardised $\delta^{13}C$ (‰) value that reflects the immediate environment in which the sample originated. With knowledge of the expected $\delta^{13}C$ value for a given environment this can be used to assess the impact of other chemical processes that have altered the ^{14}C levels of a sample since death such as recrystallization of shells, contamination, and mixing of material from differing environments (i.e. terrestrial and aquatic photosynthesisers). This provides a potential means of undertaking quality assurance of ^{14}C ages within a geochronological compilation by incorporating $\delta^{13}C$ values in assessment criteria. However, not all radiocarbon data is reported with $\delta^{13}C$ values and in some cases there may not be sufficient contextual data to make post hoc assessments of whether a $\delta^{13}C$ value is anomalous.

Another category of chemical processes particularly relevant for quality assurance of legacy data is 'reservoir effects' (Stuiver and Polach, 1977). These occur where organic material fixes carbon from a source other than the atmosphere. They can occur where carbon is sourced from rocks (hardwater effect), redeposited organic material, or from ocean water (Marine Reservoir Effect [MRE]) (Deevey et al., 1954; Mangerud and Gulliksen, 1975; Olsson, 1986).

Due to the extended residence time and large reservoir of ^{14}C within the ocean, marine samples are depleted in ^{14}C with respect to the atmosphere and, consequently, produce 'old' ^{14}C ages (the MRE). The offset between marine and terrestrial ^{14}C ages varies spatially and temporally (Fig. 6) thus there is no single, universal correction factor (Austin et al., 1995, 2011; Waelbroeck et al., 2001; Björck et al., 2003; Bondevik et al., 2006). Given the current state of knowledge some workers quote marine ^{14}C ages with bracketing maximum and minimum potential reservoir corrections (e.g. Small et al., 2013). While we acknowledge issues with establishing the precise timing of variations in the marine reservoir effect during the last deglaciation (e.g. Austin et al. (2011) tune their record to Greenland, assuming synchronicity), the magnitude of changes observed provides a reasonable guide for the choice of maximum/minimum corrections to be applied. The hardwater effect (Deevey et al., 1954) is caused by ^{14}C-depleted carbonate ions (i.e. from carbonate rocks) dissolving in freshwater and diluting the ^{14}C concentration of the dissolved inorganic carbon in the water. When this carbon is taken up by aquatic organisms their ^{14}C age is older than contemporaneous terrestrial organisms (e.g. Shotton, 1972; Child and Werner, 1999). The scale of the hardwater effect at a location can fluctuate over time due to changes in groundwater flow, the height of the water table and precipitation thus a modern analogue provides only a rough guide to what the hardwater effect may have been in the past.

A final issue relevant to consideration (i) is that an improving appreciation of the complexities of ^{14}C dating reveals that legacy ages may be erroneous due to incomplete understanding of certain issues at the time. An example of this is the application of ultrafiltration pretreatments to Palaeolithic bones which improves the accuracy of ^{14}C ages obtained. A program of re-measurement of bones dated previously has revealed significantly different, and generally older, results when ultrafiltration was used (Jacobi and Higham, 2008). Similarly, Blockley et al. (2008) find that appropriate pre-treatments are crucial for obtaining accurate ^{14}C ages in certain settings.

Consideration (ii), above, stems from the fact that organic material does not always occur in life position in close association with sediments of interest. Consideration (i) notwithstanding, ^{14}C provides accurate ages on the time of death; however, the target material potentially lived an indeterminable amount of time before or after the geological event of interest (glaciation or deglaciation in this case) introducing an inherent level of geological uncertainty. Additionally, geological processes affect the position of organic remains within a sedimentary sequence thus there can be an unknown discrepancy between a ^{14}C age and the true age of the deposit. Processes such as reworking, redeposition and time transgressive deposition result in materials being ex situ. Their effect is demonstrated by significant age differences between different datable materials from the same horizon (e.g. Heier-Nielsen et al., 1995; Grimm et al., 2009; Hågvar and Ohlson, 2013).

Materials datable by ^{14}C can be broadly categorised; a) bulk samples where organic material extracted from sediment is dated, b) microfossil samples requiring microscopy to extract, and c) macrofossil samples that can be visually identified and sampled. As each category has differing potential for being affected by the sources of geological uncertainty outlined above one approach that can be taken to conducting quality assurance of radiocarbon data-sets is the construction of radiocarbon 'inventories' (cf. Lowe et al., 2001). Such inventories consist of ^{14}C ages obtained from a variety of materials within the same horizon(s) in a sedimentary sequence (e.g. Turney et al., 2000; Walker et al., 2001, 2003; Lowe et al., 2004) allowing identification of problematic materials which yield age reversals or consistent offsets with other dates from the same horizon (e.g. Turney et al., 2000; Walker et al., 2001). Such studies have shown that the category of sample (e.g. macrofossil), and even the choice of species to be dated, can have a considerable effect on the reliability of ages (e.g. Broecker and Clark, 2011; England et al., 2013) however, their application has been relatively sparse (Lowe et al., 2001).

For the purposes of constraining ice sheet retreat the majority of ^{14}C ages within a compilation are unlikely to be part of an inventory. In this

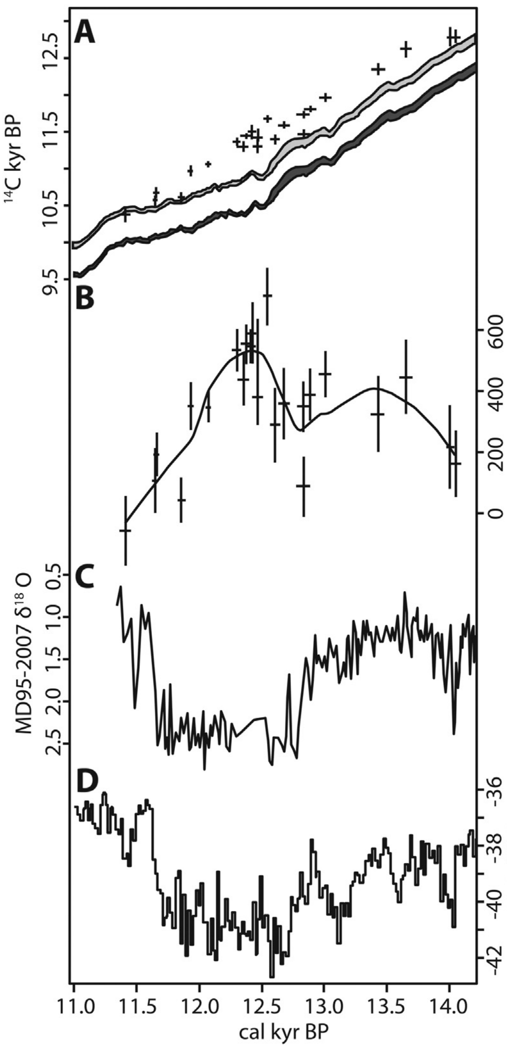

Fig. 6. (A) Discrete ^{14}C data from the St Kilda Basin (Austin et al., 2011) plotted with INTCAL09 (lower) and MARINE09 (upper) calibration curves (Reimer et al., 2009) showing the offset between radiocarbon ages derived from marine organisms and the equivalent terrestrial calibration; (B) St Kilda Basin surface ocean reservoir age (ΔR) showing its variability with time during the time period relevant to the last deglaciation; (C) St Kilda Basin (MD95-2007) $\delta^{18}O_{foram}$ record; (D) NGRIP $\delta^{18}O_{ice}$ record used to construct the age models (see Austin et al., 2011 for details). Apart from the IntCal09 and Marine09 calibration curves, all data are plotted on the equivalent NGRIP GICC05 timescale (Rasmussen et al., 2006).

case it may be most practical to base quality assurance on the general category of material that has been dated, informed by the results or radiocarbon inventories. Bulk sediment samples have the highest potential for mixing carbon of different ages and from different sources as the sample is likely to have been deposited over a period of time and, potentially, mixed by processes such as bioturbation (e.g. Kershaw, 1986). In the context of constraining deglaciation bulk samples may be particularly prone to problems with widespread re-mobilisation of potentially old carbon due to peri-glacial processes that were widespread around deglaciating margins (Lowe and Walker, 2000). ^{14}C ages obtained from microfossil samples can suffer from the translocation of water soluble humic acids in situ, although chemical pretreatment of the sample material mitigates this. What is harder to quantify and correct are reservoir effects, including the hardwater effect. Additionally, microfossil samples consist of many individual microfossils introducing potential for dating a sample of 'mixed' ages. The resulting ^{14}C age will be an average and potentially biased by incorporation of 'young' or 'old' fractions. The composition of the sample (e.g. monospecific vis a vis poly-specific) can have a significant effect on how closely this age will reflect the true age of the sediment as determined by other means (Heier-Nielsen et al., 1995). Finally, macrofossils are often considered the optimal material for dating as the influence of reservoir effects can be effectively minimised by good sample selection (Törnqvist et al., 1992; Kitagawa and van der Plicht, 1998). They can, however, still be influenced by reworking and mixing, if the sample contains more than one individual organism.

2.3. Luminescence

Luminescence dating directly determines the time of sediment deposition (burial) by determining when a mineral grain (typically quartz or K-feldspar) was last exposed to sunlight (or bleached). Exposure to sunlight prior to deposition (e.g. during transport) releases accumulated charge within light-sensitive traps in the crystal lattice of mineral grains. After burial grains are exposed to ionizing radiation caused by the presence of radioactive elements (e.g. U, Th, K) in the natural environment. This radiation excites electrons that become trapped within crystal imperfections. The concentration of radionuclides and the magnitude of the radiation dose arising from cosmic rays is assessed for each sample and the data used to calculate the magnitude of the radiation dose per year, known as the environmental dose rate. The total dose to which the grains were exposed during burial the grains (the equivalent dose; D_e) can then be determined in the laboratory and divided by the environmental dose rate to determine the time since deposition. The ubiquitous nature of the target minerals (quartz and feldspar) along with the ability to directly date sedimentary deposits has lead to luminescence being widely applied to glacially derived sediments (e.g. Owen et al., 2002; Duller, 2006; Glasser et al., 2006; Pawley et al., 2008; Smedley et al., 2016, in press).

In direct sunlight the optically stimulated luminescence signal from quartz grains can be bleached within a few seconds (Colarossi et al., 2015), however in nature the potential for bleaching is dependent on the transport and depositional pathways of the sampled sediment (Fuchs and Owen, 2008). Aeolian processes are generally considered optimal for luminescence dating as sub-aerial exposure of sediment, a pre-requisite for mobilization by wind, provides ample opportunity for exposure to light (Lancaster, 2008; Roberts, 2008). In such cases the measured D_e will accurately reflect the time of deposition of the sediment. In comparison other transport mechanisms such as fluvial and glacio-fluvial processes have reduced potential for complete bleaching (Wallinga, 2002; King et al., 2014). This is due to the turbidity of the water or length of transport that acts to reduce the potential for exposure to light (Wallinga, 2002).

The use of optical stimulation to generate optically stimulated luminescence (OSL) and the development of the single-aliquot regenerative dose (SAR) protocol by Murray and Wintle (2000) have allowed the OSL signal of quartz to be used to provide accurate and precise ages in agreement with independent chronology from a variety of depositional environments (see Roberts, 2008; Murray and Olley, 2002), including glaciofluvial settings (e.g. Duller, 2006). In contrast to quartz, luminescence dating of K-feldspars using infra-red stimulated luminescence (IRSL) has been less widely applied due mostly to the effects of anomalous fading (Wintle, 1973). However, recent improvements (Thomsen et al., 2008) have largely overcome this problem and Smedley et al. (2016) show that reliable ages can be obtained from glaciofluvial sediments.

Direct dating of material deposited by ice sheets (i.e. till) can be problematic due to the limited potential for bleaching (e.g. Lukas et al., 2007; Fuchs and Owen, 2008). However, for the purposes of constraining glaciation, OSL can be applied to sediments from a variety of settings that can be linked to former ice margin positions such as ice marginal sediments (e.g. Thomas et al., 2006), glacial lake sediments (e.g. Lepper et al., 2007) and, glaciofluvial outwash (e.g. Smedley et al., 2016). Additionally, OSL ages from sediments that are above or below glacial material provide maximum-minimum age constraints on a glacial event (e.g. Ó'Cofaigh et al., 2012; Bateman et al., 2015).

2.3.1. Obtaining an OSL age

To obtain an OSL age a sample of sediment is taken from the unit of interest. OSL measurements can be undertaken on a variety of grain sizes (e.g. ~4–11 μm or ~63–300 μm) and minerals (quartz/feldspar). Thus following sampling, the mineral and size fraction of interest are isolated using separation methods (e.g. Wintle, 1997). At all stages, from sampling to measurement, care is taken to shield the sample from exposure to anything other than red-light (to which the OSL signal is insensitive to bleaching). There are numerous approaches to making OSL analyses including variations in aliquot size measured (e.g. large aliquot, small aliquot, single-grain measurements). Grains are mounted on a disc and analysed with an OSL reader (e.g. Risø TL/OSL DA-15). The measured D_e value is combined with the environmental dose rate, calculated from measured concentrations of radioactive minerals and external gamma-dosimetry, to derive an OSL age. The measurement of multiple aliquots allows a distribution of D_e values to be obtained thus allowing statistical models to improve the accuracy of the D_e value to be used in calculating an age. Several models exist including the minimum age model (MAM; Galbraith et al., 1999) and the internal external consistency criterion (IEU) model (Thomsen et al., 2007). The choice of model to be employed depends on the observed scatter in D_e values. OSL ages are reported as years before present with $\pm 1\sigma$ uncertainties that combine random and systematic uncertainties.

Given the rapid developments in the application of OSL it is likely that a geochronological compilation will contain OSL ages produced by a variety of methods and protocols. With sufficient supporting information users of compilations can, in consultation with OSL specialists, make judgements on which measurements are suitably robust in terms of the analytical procedures adopted.

2.3.2. Sources of geological uncertainty

One potential source of geological uncertainty in OSL dating is incomplete resetting of the OSL signal during transportation and deposition (Duller, 1994, 2008); this is commonly referred to as partial bleaching. Individual grains within partially-bleached sediment are likely to have experienced variable periods of sunlight exposure for different lengths of time prior to burial. This will have reset the OSL signal of different grains to different levels, which causes scatter in D_e distributions when replicate aliquots are measured, ranging from doses representative of the last deposition cycle, up to larger (inherited) doses from grains that were never exposed to sunlight (i.e. OSL signals in saturation).

The extent of sunlight bleaching in nature is dependent on the transportation and depositional pathways of the sampled sediment (Fuchs and Owen, 2008; Livingstone et al., 2015). In fluvial and glacio-fluvial environments there is reduced potential for complete bleaching of sediment grains prior to burial (Duller, 1994). Factors such as the depth, turbidity and sediment content of the transport medium (water) can all enhance the attenuation of sunlight through the water column (Berger and Luternauer, 1987; Gemmell, 1988a, 1988b), which reduces the opportunity for bleaching of the OSL signal prior to burial, in addition to the length and number of cycles of transport.

To overcome the uncertainty introduced into luminescence dating by incomplete bleaching smaller aliquot sizes are typically used for OSL analysis (i.e. small multi-grain aliquots or single grains) because standard aliquots contain ~2500 grains and average out the effects of variable grain bleaching (Duller, 2008). Where partial bleaching may be an issue large numbers of replicate measurements (at least 50 per sample (Rodnight, 2008)) are used to characterise the distribution. Graphical representation of each distribution can be used to diagnose the presence of partial bleaching (Fig. 7). To determine an accurate age statistical models (e.g. MAM, IEU) can then be used to determine

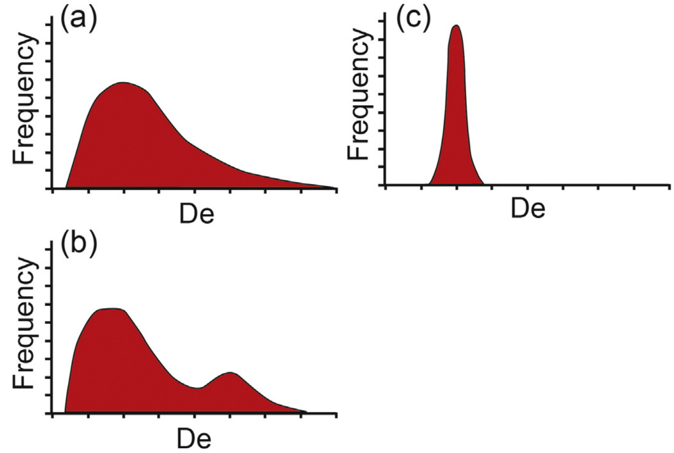

Fig. 7. Hypothetical effects of partial bleaching upon OSL replicate D_e values. (a) partially bleached sample with a continuum of D_e values from well bleached to poorly bleached (b) partially bleached samples in which poorly bleached D_e values still cluster around an inherited value (c) a well bleached sample. Adapted from Bateman et al. (2003).

the population of grains in the D_e distribution that were completely bleached prior to burial.

Bioturbation can cause post-depositional grain mixing in sediments sampled for OSL dating and manifest in complex D_e distributions containing grains that have been moved from underlying (older) and overlying (younger) sediments (e.g. Bateman et al., 2003). Identifying the effects of bioturbation on OSL dating can be challenging, however, samples taken from glaciofluvial settings typically do not experience such issues and existing sedimentary structures within the units sampled can often be used to rule-out the influence of bioturbation.

Although the potential for geological uncertainty to be introduced into luminescence dating can be identified from information provided in the legacy data, it is normally impossible to correct for these effects at a later time, and this has significant implications for the inclusion of legacy luminescence data within geochronological compilations such as BRITICE-CHRONO.

3. Assessment of the BRITICE database

All known ages relating to the last BIIS were compiled into a database by Hughes et al. (2011; the BRITICE-database v1). The published BRITICE-database v1 was updated with the inclusion of newly published data (BRITICE-database v2) with a census date of 01/01/2013 (cf. Hughes et al., 2016). The v2 database contained a total of 1231 ages (686 ^{14}C, 439 TCN, 106 OSL). The aim here was to build a new, assessed version (BRITICE-database v3) of the legacy database, in which our judgments improve on those in BRITICE-database v1/2 where all ages were taken at face value and used in a reconstruction as being of equal and high-enough reliability (Clark et al., 2012). Where the possibility of geological uncertainty is unacceptably high, the rating (confidence) that is assigned to any age is reduced.

An initial 'age filtering assessment' was carried out to focus assessment on those ages relevant to BRITICE-CHRONO where our focus is on deglaciation of the last BIIS. Implicit in this is the exclusion of later glacial events, namely the Loch Lomond Readvance (LLR). This event is temporally constrained as the local equivalent to Greenland Stadia-1 (GS-1, 12.9–11.7 ka b2k; Rasmussen et al., 2006): thus ages <13 ka were not considered for the purposes of BRITICE-CHRONO. Similarly, it is possible to place an upper boundary on ages for inclusion. As BRITICE-CHRONO is explicitly focused on retreat from the LGM it is reasonable to exclude ages that predate the maximum extent of the BIIS. Although the precise timing of this varies spatially an absolute maximum age can be assigned based on several lines of evidence. Firstly, offshore IRD suggests expansion of the BIIS into the marine realm after

29 ka (Fig. 8) (Scourse et al., 2009). Secondly ice-free conditions at c.35 ka, in areas proximal to ice nucleation centres, are evidenced by the occurrence of Pleistocene fauna whose remains have been reliably dated using ^{14}C (Jacobi et al., 2009). Taking these two lines of evidence it is considered reasonable to assume that no sector of the BIIS reached its maximum extent prior to 30 ka. As a result, ages >30 ka are also not considered for further quality assurance. Applying these two age filters significantly reduces the number of ages within the database (Table 1).

To make the best use of the BRITICE-database v2 we have developed an explicit and transparent protocol for the quality assurance carried out. An important principle was that the first assessment of an age or group of ages from any given site should be on the basis of the stratigraphic and geomorphic context and the details of the particular dating method involved. Specifically, after initial age filtering no regard should be given to whether "ages fit hypotheses" about wider regional patterns of retreat. In this way, ages were treated as measurements that were independent of the phenomena that were being investigated (Bronk Ramsey, 1998). One potential way this could have been achieved would have been to employ some form of double blind assessment where ages were multiplied by a random factor before being assessed and without the factor being known. One major difficulty however was the volume of data to be assessed and the need for sufficient stratigraphical and contextual data. Extracting and summarizing this for the entire BRITICE v2 database, while maintaining its anonymity, would have been exceptionally time consuming and was considered impractical. As the aim was to avoid basing assessment on pre-existing hypotheses of regional ice retreat, we did not define criteria that referred to other data from other locations. In doing so we judged it solely by our criteria and not with respect to pre-existing hypotheses. While this may not be as objective as a double-blind procedure we believe it balances objectivity with practicality.

By assessing data in this way we acknowledge that supporting local evidence is important, that is evidence from the same location or from nearby locations that can be reasonably assumed on stratigraphical or geomorphological grounds to have shared the same glaciological history. In effect, we need to define what we mean by a "site". In this context a "site" can be defined as either evidence from the same location or from nearby locations that can be reasonably assumed to have shared the same glaciological history. When considering multiple locations in these terms a "site" could be defined on simple proximity; i.e. any differences in the ages of deglaciation at locations within a few km's may not be resolvable given inherent dating uncertainties. A "site" could also be defined on geological evidence that allows correlation between more disparate sites. For example, in Wester Ross moraines mark the extent of a well-defined, Late Glacial readvance, the Wester Ross Readvance (Robinson and Ballantyne, 1979). These moraines can be traced over many kilometres so locations several km's apart are likely to have been deglaciated at the same time (at least within dating uncertainties), thus they can be considered to be the same feature (or "site"). Similarly in the Firth of Clyde, areally extensive deposits document a marine incursion post deglaciation (Peacock et al., 1977, 1978). The similarity of the fauna, sedimentology and their occurrence at a similar altitude imply contemporaneous deposition. Thus it could be argued that samples from these deposits, even when taken from sections several km apart, are dating the same feature ("site").

Table 1
Results of age filtering the BRITICE-database v2 to filter data not relevant to retreat of the last BIIS (i.e. <13 ka and >30 ka). * 42 ^{26}Al ages were not included as they are parallel measurements of samples analysed with ^{10}Be.

	Original database	Age filtered	% filtered
Conventional ^{14}C	330	131	38%
AMS ^{14}C	356	150	41%
TCN	397*	165	42%
OSL	106	61	58%
Total	1189	507	42%

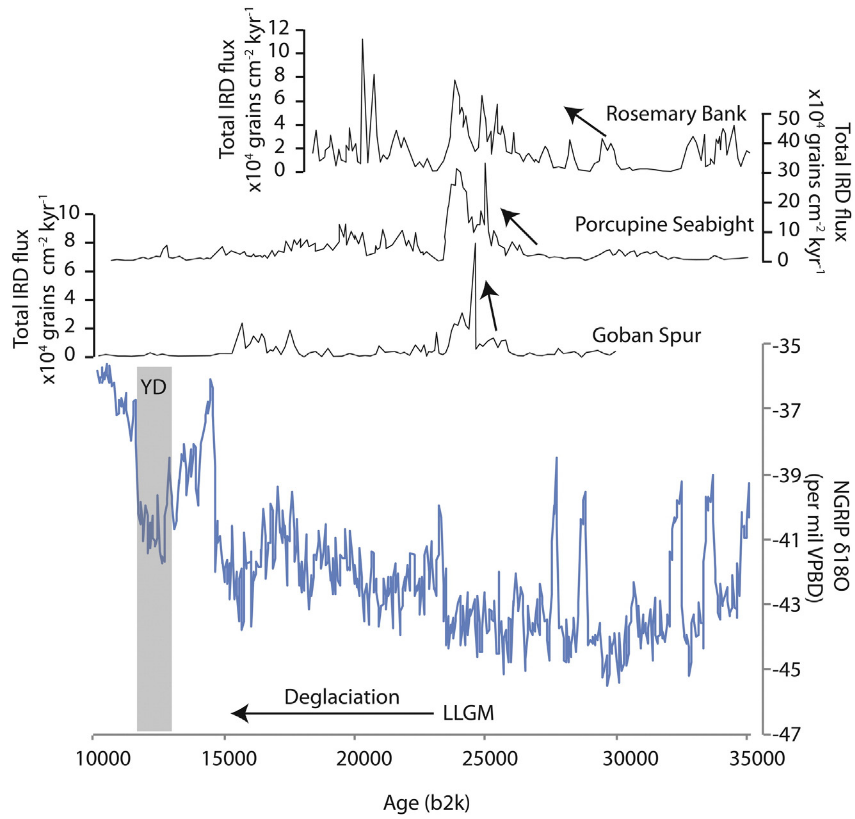

Fig. 8. IRD flux records from sites proximal to the last BIIS as compiled in Scourse et al. (2009) shown alongside NGRIP δ^{18}O record (Rasmussen et al., 2006). Increases in IRD post date 30 ka and represent advance of the BIIS onto the continental shelf towards its maximum extent.

A semi-quantitative "traffic light" system was used for the assessment of ages (Table 2). GREEN signifies ages that are considered reliable and that provide good chronological constraints on a glacially related event at a given site (i.e. deglaciation or a marine incursion). An example would be where there are multiple ages from a site/feature with those ages being consistent with each other. A first principle for an age achieving a GREEN status is that other evidence from the same site supports it.

AMBER denotes ages that are potentially reliable but which lack the weight of supporting evidence to warrant a higher status. An example of this would be where only two (internally consistent) CN ages exist from a site. Although agreement between two ages increases confidence that they are accurate it does not allow us to categorically rule out geological uncertainty. AMBER is also the status given to ages whose accuracy with respect to dating the event of interest remains uncertain due to a lack of good stratigraphical/geomorphological context.

Ages that are assigned a RED status are considered of lower reliability due to the potential for large geological uncertainty. Predominantly these are single samples with no supporting evidence from the same site making assessment of geological uncertainty difficult. In addition, sources of geological uncertainty highlighted in, or evident from, the original publication are justification for a RED status. Examples of this would be where the hard-water effect is a recognised possibility or a bulk sediment sample which possibly comprised multiple carbon sources of different ages.

3.1. Guidelines for assessing legacy data

The availability of sufficient supporting information was a first order requirement for ages generated by all techniques to be assessed and assigned a quality assurance rating (cf. Hughes et al., 2016). Sufficient supporting information was needed to allow ages to be recalculated/recalibrated as well as allowing them to be assessed for potential sources of geological uncertainty. Given the technique dependent sources of geological uncertainty outlined above, we devised the following technique specific guidelines for the consistent quality assurance assessment of the legacy data within the BRITICE-database v2. Applying these guidelines led us to define assessment criteria (Table 3) for assigning the appropriate status (GREEN, AMBER or RED) to the data within the new v3 database.

3.1.1. TCN legacy data

1) All data within a compilation to be calculated using a consistent and appropriate choice of production rate and scaling. Where data is not available for recalculation, ages will be assessed as published. Thus in our dataset ^{10}Be ages were recalculated (see Section 2.1.1) but due to insufficient data reporting ^{36}Cl ages were assessed as published.
2) As no assessment of the two primary sources of geological uncertainty (Section 2.1.2) can be made on individual samples, single samples must be treated with extreme caution and were not considered for GREEN or AMBER status.

Table 2
Definitions of quality assurance criteria.

Quality assurance rating	Definition
GREEN	Ages considered reliable and should be included in analysis. Any conflicts with new data will require to be specifically addressed.
AMBER	Ages available for inclusion in analysis. Their reliability remains open to re-assessment pending new data.
RED	Ages available for comparison with constructed retreat histories. Inclusion in analysis is dependent on new and supporting evidence.
Excluded	Assessed but judged not to make it into the screened database. This is usually because the data are outwith remit (i.e. age filtered or there is insufficient information to make an assessment).

Table 3
Quality assurance criteria used in assessment of the BRITICE-database v2.

Techniques		Criteria
Pre-requisite for all techniques		- Sufficient data to allow recalculation/recalibration
Radiocarbon	GREEN	- Multiple, consistent macrofossil/microfossil samples - Reservoir concerns addressed. - Good stratigraphic context with respect to event of interest
	AMBER	- Single macrofossil/microfossil sample - Stratigraphically consistent bulk samples - Reservoir concerns addressed. - Good stratigraphic context with respect to event of interest
	RED	- Single macrofossil/microfossil - Single bulk sample - Poor stratigraphic context with respect to event of interest
TCN	GREEN	- Multiple (3+) samples from a site - Acceptable reduced Chi-square statistic - Ages feature directly related to event of interest
	AMBER	- Only 2 internally consistent ages from a site - >2 samples not directly related event of interest
	RED	- Single samples - No internally consistent ages
Luminescence	GREEN	- A sensitivity normalized protocol was used for analysis (e.g. SAR). - Any potential for partial bleaching has been addressed using small aliquot/single grain measurements. - Supported by other geochronological data (luminescence or other method) from the same site - Good stratigraphic relationship to event of interest
	AMBER	- Potential for partial bleaching but not addressed using small aliquot/single grain measurements - Supported by other geochronological data (luminescence or other method) from the same site -Good stratigraphic relationship to event of interest - Preliminary ages or an experimental protocol was used for analyses.
	RED	- Based on feldspar without addressing the potential for anomalous fading - A single sample with no support from other geochronological data - Insufficient depositional context or details of analyses - Poor stratigraphic relationship with respect to event of interest

3) Where multiple samples exist, the consistency of the resultant ages is supported by statistical analysis. In our case we chose the χ^2_R statistic with the criterion for acceptance or rejection of any sample cluster based on Bevington and Robinson (2003). As a minimum requirement for achieving GREEN status a sample cluster must have three ages that agree within their internal (analytical) uncertainties.
4) When considering legacy data our concerns were delimiting the patterns and rates of deglaciation therefore only samples from features directly relatable to ice extent were eligible for the GREEN status. For example moraines or glacially transported boulders and not post glacial rock-fall deposits.

3.1.2. ^{14}C legacy data

1) Ages should be calibrated using the latest and most appropriate calibration curve and, in the case of marine samples, with an appropriate range of potential marine reservoir corrections. Therefore if insufficient supporting information exists to do this, data are not given further consideration (i.e. not given a rating).
2) Making an assessment about consideration i) (Section 2.2.2) required the sample material and supporting "site" information to be taken in to account.
3) Where data existed as part of a 'radiocarbon inventory' (see Section 2.2.2) the results of this were used to guide assessment. However, as most data within our database did not form part of an

inventory it was necessary to broadly categorise types of sample material and develop individual criteria for quality assurance of these. We divided sampled material into bulk samples, microfossil samples (multiple individuals) and macrofossil samples (single individuals).

4) Ages can only be properly assessed if sufficient information relating to stratigraphic context is provided in the original publication. If information is insufficient to ascertain the stratigraphical relationship ages were only eligible for the lowest, RED quality assurance rating.
5) No assumption is made regarding the reliability or precision per se between ^{14}C measurements derived from AMS or radiometric counting techniques but the nature of the sample material, where known, is considered when deciding whether to assign GREEN, AMBER or RED status to an age.
6) Given the variability in data reporting we chose not to make post hoc use of δ^{13}C. However where the original authors identify issues through the δ^{13}C value this was taken into consideration.

3.1.3. OSL legacy data

1) Given different luminescence properties, the sampled material, method and aliquot size must be taken into consideration (i.e. quartz vis a vis feldspar, standard aliquot vis a vis single grain), and whether a sensitivity normalized method such as SAR was used.
2) If samples are from a depositional context expected to have been partially-bleached prior to deposition, information must be provided that demonstrates an assessment of partial-bleaching has been made for the age to be considered reliable. Samples without this could at best be considered AMBER.
3) Ages can only be properly assessed if sufficient contextual information relating to stratigraphic context is provided in the original publication. If information is insufficient, ages were only eligible for the lowest RED quality assurance rating.

4. Quality assurance on the BRITICE-CHRONO database

The results of the quality assurance exercise undertaken on the BRITICE-database v2 database are summarized in Table 4. The overall result is that only 45 sites (23 CN, 16 ^{14}C, 6 OSL) received the highest (GREEN) quality assurance rating and are considered well-dated with respects to constraining a relevant geological event (deglaciation, marine incursion or, for modelling purposes, ice advance). A further 53 sites (19 CN, 31 ^{14}C, 3 OSL) are constrained by ages with the next highest (AMBER) quality assurance rating (Fig. 9). The assessment of data represents a significant reduction in the amount of data considered suitable for synthesis in comparison to that what was utilised in a previous reconstruction (e.g. Clark et al., 2012). The assessed database and associated metadata is available in supplementary data.

The assessed data were imported into ArcGIS v.10.1 and converted into GIS compatible files containing all of the relevant metadata and our quality assurance rating. These data are available as supplementary data in both ArcGIS (.shp) format on request and as Google Earth (.kmz) formats in supplementary data.

Overall the spatial coverage of legacy data that receives either a GREEN or AMBER status is extensive within the terrestrial extent of the former BIIS (Fig. 9). Reliable data from the marine realm are sparse with only four sites being constrained by GREEN or AMBER data. This contrast is to be expected given the restricted availability of marine sampling capabilities for much of the period when legacy data were being collected and the difficulty in obtaining good context with respect to glacial deposits. Additionally, of the three geochronological techniques, only ^{14}C has been applied to marine samples from the former BIIS and basal marine ^{14}C ages from the continental shelf must necessarily be considered as minimum deglaciation ages with an unquantifiable but intrinsic geological uncertainty between the timing of deglaciation and the deposition of the dated organic material.

Table 4
Summary of result of quality assurance carried out on BRITICE-database v2. *Total includes 42 ^{26}Al measurements that were not subject to quality assurance as they were repeat measurements of ^{10}Be samples.

	GREEN		AMBER		RED			
Technique	Sites	Ages	Sites	Ages	Sites	Ages	Age filtered	Total
TCN	23	104	19	37	–	91	165	439*
^{14}C	16	55	31	96	–	254	281	686
OSL	6	22	3	7	–	16	61	106
Totals	45	181	53	140	–	361	507	1231

The reduction of ^{14}C data available is particularly striking. One factor is that many ^{14}C data exist as parts of dated sequences recording paleoenvironmental change, thus only the basal age is directly relevant for constraining deglaciation. Additionally, only in certain stratigraphic and geomorphic scenarios will organic material be directly relatable to glacial deposits and eligible for the highest quality assurance rating, an example being organic material reworked into till, or organic deposits stratigraphically over- or under-lying till (e.g. McCabe et al., 2007; Ó'Cofaigh and Evans, 2007). We emphasise that other scenarios where basal ages are not directly relatable to glacial deposits, and are thus assigned a lower quality assurance rating, do not make 'bad data'. This is manifest in the many sites that are assigned an AMBER quality assurance rating. We anticipate a significant contribution from AMBER data in providing boundary constraints in future reconstructions and modelling experiments.

TCN can directly date onshore features related to ice margins, such as moraines (e.g. Bradwell et al., 2008; Ballantyne et al., 2009b; Small et al., 2012, 2016) glacially transported boulders (e.g. Everest et al., 2013; Fabel et al., 2012), and ice dammed lake shorelines (e.g. Fabel et al., 2010). The TCN technique accounts for the largest number of well dated sites following quality assurance. Although 42 ^{26}Al ages were included in the BRITICE-database v2 all of these were employed as tests for complex exposure histories alongside parallel ^{10}Be measurements. They thus provide useful information about glaciation styles and erosion but do not offer additional constraints on the timing of deglaciation. In comparison to ^{14}C and TCN, luminescence ages make up a smaller component of the BRITICE-database v2.

5. Towards a Bayesian approach to modelling deglaciation

The quality assurance procedures outlined above treat ages individually, within our definition of a site (Section 3), such that they are considered as independent measurements (Bronk Ramsey, 1998). However, in the context of geological reconstructions these ages exist within a spatial and temporal framework. This concept is in part illustrated by the stratigraphic principle of superposition where, barring turbation or tectonics, a lower layer within a stratigraphic sequence cannot be younger than any overlying layer. This allows the sequence of events (geomorphological features or sedimentary units), the 'prior' model' in Bayesian terminology, to be determined independently of the chronological measurements (Buck et al., 1996; Bronk Ramsey, 2008; Chiverrell et al., 2013). This independently constructed relative order of events (prior model) contains a series of also independent age measurements often with overlapping age probability distributions, and provides a basis for using Bayesian age modelling (Buck et al., 1996; Bronk Ramsey, 2008) to assess the conformability of the age measurements and generate a model output of the timing of events within a sequence. The use of Bayesian age modelling (Buck et al., 1996; Bronk Ramsey, 2008) has several advantages; particularly the robust handling of outliers (Bronk Ramsey, 2009a, 2009b) and ability to reduce modelled age uncertainties (Blockley et al., 2007; Chiverrell et al., 2013). It is the intention of the BRITICE-CHRONO project to use Bayesian age modelling to produce glacial chronologies that will subsequently be used to test agreement between data and numerical ice sheet models. This Bayesian age modelling will be informed by the quality assurance protocols outlined in this contribution and we thus outline our approach. In doing so we test a previous application of Bayesian age modelling to the British-Irish Ice Sheet (Chiverrell et al., 2013).

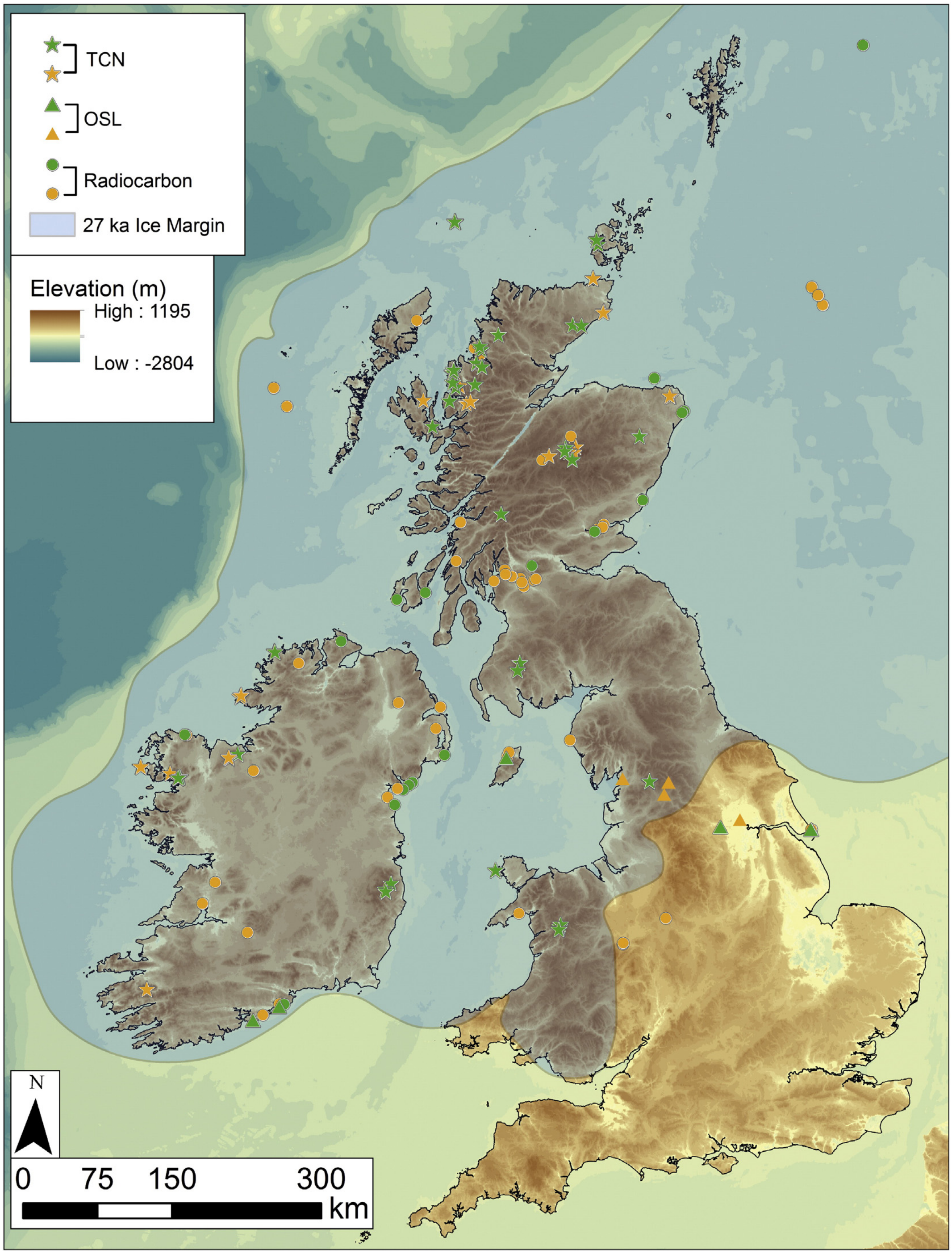

Fig. 9. Map of the legacy data from BRITICE-database v2 that has undergone quality assurance and been assigned a GREEN or AMBER rating. Displayed ice sheet margin at 27 ka is from DATED-1 (Hughes et al., 2016). Background elevation data from gebco.net. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When used in the context of constraining glacial chronologies the prior model consists of a sequence of locations arranged in the order they would have been deglaciated. For ice sheets, ice streams, and glaciers this sequence can be determined on glaciological grounds (e.g. deglaciation proceeds from ablation zone to accumulation zone) and geomorphological grounds (e.g. using indicators of past ice flow direction). This a priori knowledge allows sites to be arranged in spatial sequence of ice-marginal retreat (cf. Chiverrell et al., 2013). Additional constraints from relative dating information can be incorporated in the prior model by considering the stratigraphic relationship between ages and the event of interest. So for example, ^{14}C ages from marine deposits stratigraphically above till provide a minimum age for deglaciation. This limiting age constraint (terminus ante quem in Bayesian terminology) sits within the spatial sequence and informs that a site was deglaciated before a certain time (to be defined by the ages from that particular site). The prior model is generated without reference to any age determinations such that it is independent of the numerical dating information.

Chiverrell et al. (2013) used a Bayesian approach to age model retreat of the Irish Sea Ice Stream, one of the largest ice streams to drain the former BIIS. The dating control used in this effort was drawn from the literature with quality assurance applied in a more piecemeal

```
Options()
{
 BCAD=FALSE;
 PlusMinus=FALSE;
 SD1=FALSE;
 SD2=TRUE;
 SD3=FALSE;
 ConvergenceData=TRUE;
 kIterations=100;
};
Plot()
{
 Outlier_Model("ISIS", T(5), U(0,4),
t);
 Sequence("Irish Sea")
 {
  Boundary("Start Irish Sea Model");
  After("Pre-MIS 2 LGM")
  {
   Phase("Sourlie")
   {
    R_Date("Sourlie L2", 29900, 430)
    {
     color="Green";
     Outlier(0.05);
    };
    R_Date("Sourlie L1", 29290, 350)
    {
     color="Green";
     Outlier(0.05);
    };
   };
   Phase("Balglass")
   {
    R_Date("CAMS72408", 30080,
200)
    {
     color="Green";
     Outlier(0.05);
    };
    R_Date("CAMS72405", 28050,
160)
    {
     color="Green";
     Outlier(0.05);
    };
   };
  };
  Boundary("Advance ISB");
  Phase("Ardmore, Whiting,
Garryvoe")
  {
   R_Date("Beta-215778", 22075, 90)
   {
    Outlier(0.2);
    color="Yellow";
   };
   R_Date("Beta-222306", 23025,
150)
   {
    color="Yellow";
    Outlier(0.2);
   };
   R_Date("Beta-222305", 20295,
120)
   {
    Outlier(0.05);
    color="Green";
   };
   R_Date("Beta-222304", 21135,
130)
   {
    Outlier(0.05);
    color="Green";
   };
   R_Date("Beta-215772", 20775, 80)
   {
    Outlier(0.05);
    color="Green";
   };
   R_Date("Beta-215771", 20185, 70)
   {
    Outlier(0.05);
    color="Green";
   };
  };
  Boundary("Advance South
Ireland");
  After("Carn Morval")
  {
   R_Date("Carn Morval", 21500, 890)
   {
    Outlier(1);
    color="Red";
   };
  };
  Boundary("LGM Scilly");
  Phase("Tregarthen")
  {
   C_Date("Tregarthen1", 22700, 900)
   {
    Outlier(1);
    color="Red";
   };
   C_Date("Tregarthen2", 25100,
2200)
   {
    Outlier(1);
    color="Red";
   };
  };
  Before("Scilly Isles CN dating")
  {
   C_Date("Shipman Head1", 22075,
1076)
   {
    Outlier(1);
    color="Red";
   };
  };
  Boundary("Retreat South Ireland");
  Phase("OSL Waterford")
  {
   C_Date("Ballcroneen2", 21600,
2100)
   {
    color="Green";
    Outlier(0.05);
   };
   C_Date("Ballcroneen1", 23000,
2100)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("Whiting Bay2", 24200,
2300)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("Whiting Bay1", 24400,
1800)
   {
    Outlier(0.05);
    color="Green";
   };
  };
  Boundary("Retreat Wexford");
  C_Date("Screen Hills", 23600, 2400)
  {
   Outlier(0.2);
   color="Yellow";
  };
  Boundary("Wicklow-llyn I");
  C_Date("Mottee Stone", 22300,
2000)
  {
   Outlier(1);
   color="Red";
  };
  Boundary("Wicklow-llyn II");
  C_Date("Nefyn", 21300, 2200)
  {
   Outlier(0.2);
   color="Yellow";
  };
  Boundary("Wicklow-llyn III");
  Phase("Mynydd Mawr")
  {
   C_Date("MM2", 22380, 1047)
   {
    Outlier(0.2);
    color="Yellow";
   };
   C_Date("MM1", 23746, 1010)
   {
    color="Yellow";
    Outlier(0.2);
   };
  };
  Boundary("Retreat towards
Anglesey");
  Phase("K Steps")
  {
   R_Date("Kershaw1", 20040, 610)
   {
    Outlier(1);
    color="Red";
   };
   R_Date("Kershaw2", 19210, 690)
   {
    Outlier(1);
    color="Red";
   };
  };
  Boundary("Retreat Kilkeel");
  Before("Kilkeel")
  {
   Phase("K Steps")
   {
    R_Date("Kilkeel steps1b", 17150,
160)
    {
     Outlier(0.05);
     color="Green";
    };
    R_Date("Kilkeel steps1a", 17160,
130)
    {
     Outlier(0.05);
     color="Green";
    };
    R_Date("Kilkeel steps2", 17040,
70)
    {
     Outlier(0.05);
     color="Green";
    };
    R_Date("Kilkeel steps3", 16940,
70)
    {
     Outlier(0.05);
     color="Green";
    };
    R_Date("Kilkeel steps4", 17370,
190)
    {
     Outlier(0.05);
     color="Green";
    };
   };
  };
  Boundary("Bracketing Anglesey");
  Phase("Anglesey1")
  {
   C_Date("HM-01", 21483, 1023)
   {
    color="Yellow";
    Outlier(0.2);
   };
   C_Date("HM-02a", 18777, 852)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("HM-03", 19502, 929)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("HM-02b", 19782, 1019)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("HM-04", 18620, 781)
   {
    Outlier(0.05);
    color="Green";
   };
  };
  Boundary("Killard Point re-
advance");
  Before("Killard Point")
  {
   R_Date("Killard Point2", 13785,
115)
   {
    Outlier(0.05);
    color="Green";
   };
   R_Date("Killard Point1", 13995,
105)
   {
    Outlier(0.05);
    color="Green";
   };
  };
  Phase("IoM")
  {
   C_Date("OR14(90-125)", 14100,
2100)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("OR14(200-250)", 14400,
2300)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("OR15(90-125)", 14200,
2300)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("OR22(150-180)", 15200,
1600)
   {
    Outlier(0.05);
    color="Green";
   };
   C_Date("OR22(150-180)", 15200,
1600)
   {
    Outlier(0.05);
    color="Green";
   };
  };
  Boundary("Late glacial warming");
  Before("Kettle sites")
  {
   Phase("Basal kettlehole sites")
   {
    R_Date("Jurby", 12276, 45)
    {
     Outlier(0.05);
     color="Green";
    };
    R_Date("Glen Balleira", 12492, 95)
    {
     Outlier(0.05);
     color="Green";
    };
   };
  };
  Boundary("End");
 };
};
```

Fig. 10. Model specification (OxCal input code) for Irish Sea Ice Stream Bayesian age model.

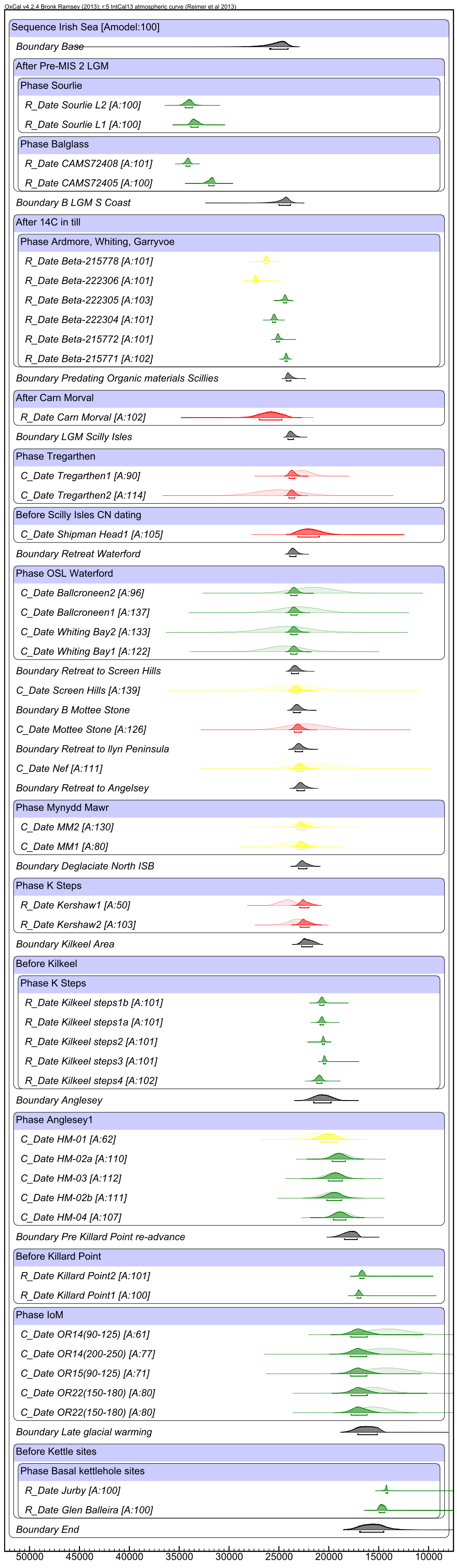

Fig. 11. Bayesian age model output from OxCal 4.2 (Bronk Ramsey, 2013) colour coded according to our assessment criteria (Yellow = AMBER). The likelihood probabilities are light colours, posterior probabilities are darker. Bars are 1σ uncertainties. Agreement indices (A) for individual samples are shown highlighting the conformability of some RED data.

manner. The Bayesian approach allows the identification of outliers by comparing the overlap between the likelihood probability distribution and the modelled posterior probability distribution (Bronk Ramsey, 2009a). Chiverrell et al. (2013) assigned outlier measurements a prior probability of being an outlier (probabilities ranging from 0.1 to 1) thereby reducing or excluding their impact on subsequent model runs. This approach produced a conformable age model for the Irish Sea Ice Stream retreat sequence (Fig. 2 in Chiverrell et al. (2013)) with overall model agreement indices >98% exceeding the >60% threshold advocated by Bronk Ramsey (2009a).

As an experiment we re-ran the Bayesian age model of the Irish Sea Ice Stream using the same initial dating control, but with all measurements assigned a probability of being an outlier using our quality control screening. GREEN data were assigned a prior probability of 0.05 (i.e. 1 in 20) and AMBER data 0.2 (i.e. 1 in 5). RED data were assigned a prior probability of 1 for being an outlier. The Bayesian modelling was undertaken in OxCal 4.2 (Bronk Ramsey, 2013) using a uniform phase model and run as an outlier model (Buck et al., 1991; Bronk Ramsey, 2009a). The models were set up to assess for outliers in time (t), which is appropriate given the range of dating techniques incorporated. We used a student's t-distribution to define how the outliers are distributed and a scale of 10^0–10^4 years (cf. Bronk Ramsey, 2009a). The models make the following assumptions:

1. Deglaciation is a progressive process that cannot occur in two places at precisely the same time.
2. There is a constant retreat rate between dated sites. This is akin to assuming a linear sedimentation rate within a depositional sequence.
3. All ages from a given site are dating the same event.
4. Ages provided by different techniques (i.e.^{14}C, CN, OSL) are directly comparable.
5. All radiocarbon calibrations are an accurate conversion of a radiocarbon measurement to a calendar age.

The model uses a uniform prior (Bronk Ramsey, 2009a, 2009b) which makes several assumptions regarding calibration of ^{14}C ages (Blockley et al., 2007), however given the timespan of our model (~8 ka) and the uncertainties associated with other dating techniques any error introduced by these assumptions is not significant (cf. assumption 5). ^{14}C measurements on marine fossils received a uniform reservoir correction of 525 years. Additionally, use of the uniform prior is considered appropriate to satisfy assumption 1, that is events (ice marginal limits) can abut but cannot overlap. A linear interpolation between dated sites (assumption 2) is also implicit in the use of the uniform prior. With a large number of ages this assumption can be considered approximately true (Telford et al., 2004). Additionally, the model approach was designed to investigate large scale controls on retreat rates (e.g. bathymetry, trough width) and for this purpose a linear interpolation is appropriate. Assumptions 1 and 2 have the effect that the Bayesian age model calculates time averaged retreat rates between two age groupings but does not incorporate any variation in retreat rates within that interval. Given assumption 3, groupings of ages (phases) are classified as being ages from defined sites which can reasonably be assumed to share a glaciological history (Section 3). Phases are delimited by boundaries as this allows events to abut but not overlap. Additionally, as the dating control available comes from disparate locations the use of boundaries corrects for bias within the OxCal program that can be introduced by major gaps within a sequence (Blockley et al., 2004). Finally, calibrated ^{14}C ages are not, sensu stricto, directly comparable to CN or OSL ages as they are reported in reference to a fixed datum (1950 AD) whereas CN/OSL ages are reported as years before present (i.e. years before sampling). However, given the uncertainties associated with these techniques compared to ^{14}C and the timescales being investigated we consider assumption 4 to be valid. Our model specification is shown in Fig. 10.

The results of the age modelling are shown in Fig. 11. The input data produced a conformable sequence with modelled posterior outlier

Table 5
Prior and modelled posterior outlier probabilities for all geochronological data included in the Irish Sea Ice Stream Bayesian age model.

Data	Prior	Posterior	Data	Prior	Posterior
Sourlie L2	0.05	0.05	MM1	0.20	0.21
Sourlie L1	0.05	0.05	Kershaw1	1.00	1.00
CAMS72408	0.05	0.04	Kershaw2	1.00	1.00
CAMS72405	0.05	0.04	Kilkeel steps1b	0.05	0.04
Beta-215778	0.20	0.27	Kilkeel steps1a	0.05	0.05
Beta-222306	0.20	0.49	Kilkeel steps2	0.05	0.04
Beta-222305	0.05	0.04	Kilkeel steps3	0.05	0.05
Beta-222304	0.05	0.04	Kilkeel steps4	0.05	0.04
Beta-215772	0.05	0.04	HM-01	0.20	0.26
Beta-215771	0.05	0.06	HM-02a	0.05	0.04
Carn Morval	1.00	1.00	HM-03	0.05	0.04
Tregarthen1	1.00	1.00	HM-02b	0.05	0.04
Tregarthen2	1.00	1.00	HM-04	0.05	0.04
Shipman Head1	1.00	1.00	Killard Point2	0.05	0.04
Ballcroneen2	0.05	0.05	Killard Point1	0.05	0.04
Ballcroneen1	0.05	0.05	OR14(90–125)	0.05	0.05
Whiting Bay2	0.05	0.05	OR14(200–250)	0.05	0.05
Whiting Bay1	0.05	0.05	OR15(90–125)	0.05	0.05
Screen Hills	0.20	0.19	OR22(150–180)	0.05	0.05
Mottee Stone	1.00	1.00	OR22(150–180)	0.05	0.05
Nefyn	0.20	0.19	Jurby	0.05	0.03
MM2	0.20	0.17	Glen Balleira	0.05	0.04

probabilities shown in Table 5. The overall results are broadly similar and produced general agreement between modelled boundary ages for both approaches (Table 6). Notably, the age modelled boundaries are consistently better constrained when using the screened data. In all cases this improvement is ≥0.5 ka (Table 6). This demonstrates that, in this particular case, the original results were primarily controlled by the availability of good quality data in key locations.

RED data did not contribute to the overall model result (outlier probability = 1) however, they are conformable within the model (i.e. they have age probability distributions that overlap). It is now known that some of the RED data included in this analysis is unsound. For example the ^{10}Be exposure from Shipman Head (C_date Shipman Head1; McCarroll et al., 2010) is now known to be too old due to a significant muonic contribution to its ^{10}Be inventory from previous long-term exposure (Smedley et al., submitted). In the case of at least some of the RED data, the fact that they are conformable within the Irish Sea sequence is likely to be purely felicitous. Such erroneous yet conformable data could make a significant contribution to an age model and influence subsequent interpretations and would not be identifiable using Bayesian outlier detection alone. To remove this type of data from analysis requires a manual approach to detecting potentially unreliable data, such as that outlined here. Additionally, it demonstrates that obtaining good quality data from sites is critical to maximising the potential for applying Bayesian age modelling to glacial sequences. This is particularly the case as the relatively large uncertainties of techniques such as CN and OSL (compared to ^{14}C) mean that there is a larger possibility that some part of the likelihood probability distribution will be conformable. A combination of a manual approach to outlier detection and a model averaging approach that weights data according to how likely they are to be correct (cf. Bronk Ramsey, 2009a) produces a robust procedure for identifying potentially erroneous data and subsequently minimising its influence. A final advantage of the Bayesian approach is that when an age that has not received the highest quality rating has a lower modelled posterior probability of being an outlier than originally assigned then increased confidence can be had that said age is accurate and not affected by significant geological uncertainty.

6. Conclusions

The process of assessing the legacy BRITICE-CHRONO v2 database emphasises the importance of adequate data reporting for maximising the utility of legacy data for future workers (e.g. Stuiver and Polach, 1977; Balco et al., 2008; Dunai and Stuart, 2009; Frankel et al., 2010; Millard, 2014). While each technique has different specifics the inclusion of sufficient methodological and laboratory information to allow ages to be recalculated/updated as understanding of techniques improves (e.g. CN production rates, ^{14}C calibration) is important as, where such data is missing and cannot be obtained otherwise, legacy data can become obsolete and important information revealed by it lost. Complete reporting of how samples were processed and all associated measurements made can allow detection of issues such as contamination as techniques develop. In addition to technical information, future workers require sufficient observational information to allow some post hoc assessment of the context of samples. While individual studies are likely to make different judgements as to what observational information is important workers should be mindful that, in the future, their results may be revisited with different aims in mind and the inclusion of as much information as reasonably possible would be advantageous.

Beyond the issue of data reporting, the procedures outlined in this review highlight some general points regarding sampling strategies for studies interested in constraining glacial chronologies. It is clear from the Bayesian age model presented in Section 6 that single ages can be problematic. While they are difficult to assess for geological uncertainty and have always been treated with the most scepticism their inclusion in a prior model allows the Bayesian approach to identify

Table 6
Comparison of modelled boundary ages from Bayesian modelling of the Irish Sea Ice Stream. Original boundary ages from Chiverrell et al. (2013). Boundaries in italics are bounded by data assigned as full outliers. ISB = Irish Sea Basin.

Bayesian boundaries	Boundary ages (ka)		Difference (ka)
	Chiverrell et al. (2013)	Using screened data	
Boundary Start Irish Sea Model	31.1–26.3	29.0–25.5	1.3
Boundary Advance ISB	28.9–26.2	28.0–26.2	0.9
Boundary Advance South Ireland	24.3–23.5	24.3–24.0	0.5
Boundary LGM Scilly	24.2–23.0	24.2–23.7	0.7
Boundary Retreat South Ireland	24.0–22.7	24.0–23.4	0.7
Boundary Retreat Wexford	23.8–22.4	23.7–23.1	0.8
Boundary Retreat Wicklow-Llyn I	23.6–22.0	23.6–22.9	0.9
Boundary Retreat Wicklow-Llyn II	23.4–21.7	23.4–22.6	0.9
Boundary Retreat Wicklow-Llyn III	23.1–21.4	23.2–22.4	0.9
Boundary Retreat towards Angelsey	22.8–21.0	23.0–22.1	0.9
Boundary Retreat Kilkeel	22.3–20.5	22.6–21.5	0.7
Boundary Bracketing Angelsey	21.8–18.9	21.5–19.7	1.1
Boundary Killard Point re-advance	19.2–17.0	18.4–17.1	0.9
Boundary Late Glacial warming	17.6–14.5	16.7–14.9	1.3
Boundary End Irish Sea Model	17.6–12.3	16.6–14.1	2.8

outliers in time however, it cannot identify erroneous but conformable data. While such data may have little effect on large scale reconstructions, on more local/regional scales it could produce deglacial chronologies that do not accurately reflect the timing of deglaciation in certain locations. This could, for example, lead to incorrect estimates of retreat rates. Consequently, where material and resources exist, focus should always be on obtaining multiple ages from a site. Where this is not possible isolated ages can be assessed using technique specific criteria to identify the potential for geological uncertainty before inclusion in any subsequent synthesis. Similarly, the Bayesian age model highlights the importance of having well dated sites (e.g. with a good clustering of ages) as it is these that dominate the age model.

Finally, this paper outlines our approach to undertaking quality assurance for dating ice sheet retreat. Future studies will implicitly begin from different starting points both in terms of the number and type of data available and how (or if) that data has been compiled. While the issues regarding geological uncertainty are ubiquitous the choices made in how these issues are addressed with respects to legacy data will be subject to some degree of subjectivity. Consequently, we are outlining our criteria as an example of how a quality assurance process for dating ice sheet retreat can be undertaken and to document a decision making process for a data-set that will be used to inform a substantial body of further work. We hope doing so encourages further consideration of the quality assurance issue for the palaeo-ice sheet community.

Acknowledgements

This work was supported by the UK Natural Environment Research Council consortium grant BRITICE-CHRONO NE/J009768/1. We would like to acknowledge all of the workers who have generated the geochronological data, for whatever purpose, that comprises the BRITICE-CHRONO database. Two anonymous reviewers provided considered and thoughtful comments and advice that greatly improved this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.earscirev.2016.11.007. These data include the Google map of the most important areas described in this article.

References

André, M.F., 2002. Rates of postglacial rock weathering on glacially scoured outcrops (Abisko–Riksgränsen area, 68° N). Geogr. Annal. Ser. A Phys. Geogr. 84, 139–150.
Arnold, J.R., Libby, W.F., 1951. Radiocarbon dates. Science 113, 111–120.
Austin, W.E., Bard, E., Hunt, J.B., Kroon, D., Peacock, J.D., 1995. The ^{14}C age of the Icelandic Vedde Ash: implications for Younger Dryas marine reservoir age corrections. Radiocarbon 37, 53–62.
Austin, W.E., Telford, R.J., Ninnemann, U.S., Brown, L., Wilson, L.J., Small, D., Bryant, C.L., 2011. North Atlantic reservoir ages linked to high Younger Dryas atmospheric radiocarbon concentrations. Glob. Planet. Chang. 79, 226–233.
Balco, G., 2011. Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990–2010. Quat. Sci. Rev. 30, 3–27.
Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from 10 Be and 26 Al measurements. Quat. Geochronol. 3, 174–195.
Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. Quat. Geochronol. 4, 93–107.
Ballantyne, C.K., 2010. Extent and deglacial chronology of the last British–Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. J. Quat. Sci. 25, 515–534.
Ballantyne, C.K., Stone, J.O., Fifield, L.K., 2009a. Glaciation and deglaciation of the SW Lake District, England: implications of cosmogenic 36 Cl exposure dating. Proc. Geol. Assoc. 120 (p), 139–144.
Ballantyne, C.K., Schnabel, C., Xu, S., 2009b. Readvance of the last British–Irish ice sheet during Greenland interstade 1 (GI-1): the Wester Ross readvance, NW Scotland. Quat. Sci. Rev. 28, 783–789.
Barrows, T.T., Lehman, S.J., Fifield, L.K., De Deckker, P., 2007. Absence of cooling in New Zealand and the adjacent ocean during the Younger Dryas chronozone. Science 318, 86–89.
Bateman, M.D., Frederick, C.D., Jaiswal, M.K., Singhvi, A.K., 2003. Investigations into the potential effects of pedoturbation on luminescence dating. Quat. Sci. Rev. 22, 1169–1176.
Bateman, M.D., Evans, D.J.A., Buckland, P.C., Connell, E.R., Friend, R.J., Hartmann, D., Moxon, H., Fairburn, W.A., Panagiotakopulu, E., Ashurst, R.A., 2015. Last glacial dynamics of the Vale of York and North Sea Lobes of the British and Irish Ice Sheet. Proc. Geol. Assoc. 126 (p), 712–730.
Bentley, M.J., Fogwill, C.J., Kubik, P.W., Sugden, D.E., 2006. Geomorphological evidence and cosmogenic 10Be/26Al exposure ages for the Last Glacial Maximum and deglaciation of the Antarctic Peninsula Ice Sheet. Geol. Soc. Am. Bull. 118, 1149–1159.
Bentley, M.J., Cofaigh, C.Ó., Anderson, J.B., Conway, H., Davies, B., Graham, A.G., Hillenbrand, C.D., Hodgson, D.A., Jamieson, S.S., Larter, R.D., Mackintosh, A., 2014. A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum. Quat. Sci. Rev. 100, 1–9.
Berger, G.W., Eyles, N., 1994. Thermoluminescence chronology of Toronto-area Quaternary sediments and implications for the extent of the midcontinent ice sheet (s). Geology 22, 31–34.
Berger, G.W., Luternauer, J.J., 1987. Preliminary fieldwork for thermoluminescence dating studies at the Fraser River delta, British Columbia. Geol. Surv. Can. Pap. 87, 901–904.
Bevington, P.R., Robinson, D.K., 2003. Data Reduction and Error Analysis. McGraw-Hill.
Bird, M.I., Ayliffe, L.K., Fifield, L.K., Turney, C.M., Cresswell, R.G., Barrows, T.T., David, B., 1999. Radiocarbon dating of "old" charcoal using a wet oxidation, stepped-combustion procedure. Radiocarbon 41, 127–140.
Björck, S., Koç, N., Skog, G., 2003. Consistently large marine reservoir ages in the Norwegian Sea during the Last Deglaciation. Quat. Sci. Rev. 22, 429–435.
Blockley, S.P.E., Pinhasi, R., 2011. A revised chronology for the adoption of agriculture in the Southern Levant and the role of Lateglacial climatic change. Quat. Sci. Rev. 30, 98–108.
Blockley, S.P., Lowe, J.J., Walker, M.J., Asioli, A., Trincardi, F., Coope, G.R., Donahue, R.E., 2004. Bayesian analysis of radiocarbon chronologies: examples from the European Late-glacial. J. Quat. Sci. 19, 159–175.
Blockley, S.P.E., Blaauw, M., Ramsey, C.B., van der Plicht, J., 2007. Building and testing age models for radiocarbon dates in Lateglacial and Early Holocene sediments. Quat. Sci. Rev. 26, 1915–1926.
Blockley, S.P.E., Bronk Ramsey, C., Higham, T.F.G., 2008. The Middle to Upper Paleolithic transition: dating, stratigraphy, and isochronous markers. J. Hum. Evol. 55, 764–771.
Boaretto, E., Bryant, C., Carmi, I., Cook, G., Gulliksen, S., Harkness, D., Heinemeier, J., McClure, J., McGee, E., Naysmith, P., Possnert, G., 2002. Summary findings of the fourth international radiocarbon intercomparison (FIRI)(1998–2001). J. Quat. Sci. 17, 633–637.
Bondevik, S., Mangerud, J., Birks, H.H., Gulliksen, S., Reimer, P., 2006. Changes in North Atlantic radiocarbon reservoir ages during the Allerød and Younger Dryas. Science 312, 1514–1517.
Bradwell, T., Fabel, D., Stoker, M., Mathers, H., McHargue, L., Howe, J., 2008. Ice caps existed throughout the Lateglacial Interstadial in northern Scotland. J. Quat. Sci. 23, 401–407.
Brauer, A., Hajdas, I., Blockley, S.P., Bronk Ramsey, C., Christl, M., Ivy-Ochs, S., Moseley, G.E., Nowaczyk, N.N., Rasmussen, S.O., Roberts, H.M., Spötl, C., 2014. The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval. Quat. Sci. Rev. 106, 47–66.
Briner, J.P., Swanson, T.W., 1998. Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet. Geology 26, 3–6.
Briner, J.P., Miller, G.H., Davis, P.T., Bierman, P.R., Caffee, M., 2003. Last Glacial Maximum ice sheet dynamics in Arctic Canada inferred from young erratics perched on ancient tors. Quat. Sci. Rev. 22, 437–444.
Broecker, W., Clark, E., 2011. Radiocarbon-age differences among coexisting planktic foraminifera shells: The Barker Effect. Paleoceanography 26, PA2222.
Bronk Ramsey, C., 1998. Probability and dating. Radiocarbon 40, 461–474.
Bronk Ramsey, C., 2008. Deposition models for chronological records. Quat. Sci. Rev. 27, 42–60.
Bronk Ramsey, C., 2009a. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.
Bronk Ramsey, C., 2009b. Dealing with outliers and offsets in radiocarbon dating. Radiocarbon 51, 1023–1045.
Bronk Ramsey, C., 2013. OxCal 4.2. Manual [online] available at:. https://c14.arch.ox.ac.uk/oxcalhelp/hlp_contents.html.
Buck, C.E., Kenworthy, J.B., Litton, C.D., Smith, A.F.M., 1991. Combining archaeological and radiocarbon information: a Bayesian approach to calibration. Antiquity 65, 808–821.
Buck, C.E., Cavanagh, W.G., Litton, C.D., 1996. Bayesian Approach to Interpreting Archaeological Data. Wiley.
Child, J.K., Werner, A., 1999. Evidence for a hardwater radiocarbon dating effect, Wonder Lake, Denali national park and preserve, Alaska, USA. Géog. Phys. Quatern. 53, 407–411.
Chiverrell, R.C., Thrasher, I.M., Thomas, G.S., Lang, A., Scourse, J.D., van Landeghem, K.J., Mccarroll, D., Clark, C.D., Cofaigh, C.Ó., Evans, D.J., Ballantyne, C.K., 2013. Bayesian modelling the retreat of the Irish Sea ice stream. J. Quat. Sci. 28, 200–209.
Clark, C.D., 2014. BRITICE-CHRONO: Constraining Rates and Style of Marine-Influenced Ice Sheet Decay to Provide a Data-Rich Playground for Ice Sheet Modellers. EGU General Assembly Conference Abstracts vol. 16, p. 4266.
Clark, C.D., Hughes, A.L., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. Quat. Sci. Rev. 44, 112–146.
Colarossi, D., Duller, G.A.T., Roberts, H.M., Tooth, S., Lyons, R., 2015. Comparison of paired quartz OSL and feldspar post-IR IRSL dose distributions in poorly bleached fluvial sediments from South Africa. Quat. Geochronol. 30, 233–238.

Colgan, P.M., Bierman, P.R., Mickelson, D.M., Caffee, M., 2002. Variation in glacial erosion near the southern margin of the Laurentide Ice Sheet, south-central Wisconsin, USA: implications for cosmogenic dating of glacial terrains. Geol. Soc. Am. Bull. 114, 1581–1591.
Craig, H., 1953. The geochemistry of the stable carbon isotopes. Geochim. Cosmochim. Acta 3, 53–92.
Deevey, E.S., Gross, M.S., Hutchinson, G.E., Kraybill, H.L., 1954. The natural C14 contents of materials from hard-water lakes. Proc. Natl. Acad. Sci. 40 (p), 285–288.
Denton, G.H., Hendy, C.H., 1994. Younger Dryas age advance of Franz Josef glacier in the southern Alps of New Zealand. Science 264, 1434–1437.
Duller, G.A.T., 1994. Luminescence dating of poorly bleached sediments from Scotland. Quat. Sci. Rev. 13, 521–524.
Duller, G.A.T., 2006. Single grain optical dating of glacigenic deposits. Quat. Geochronol. 1, 296–304.
Duller, G.A.T., 2008. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. Boreas 37, 589–612.
Duller, G.A.T., Wintle, A.G., Hall, A.M., 1995. Luminescence dating and its application to key pre-Late Devensian sites in Scotland. Quat. Sci. Rev. 14, 495–519.
Dunai, T.J., 2010. Cosmogenic Nuclides: Principles, Concepts and Applications in the Earth Surface Sciences. Cambridge University Press.
Dunai, T.J., Stuart, F.M., 2009. Reporting of cosmogenic nuclide data for exposure age and erosion rate determinations. Quat. Geochronol. 4, 437–440.
Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. Dev. Quat. Sci. 2, 373–424.
Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., Veillette, J.J., 2002. The Laurentide and Innuitian ice sheets during the last glacial maximum. Quat. Sci. Rev. 21, 9–31.
England, J., Dyke, A.S., Coulthard, R.D., Mcneely, R., Aitken, A., 2013. The exaggerated radiocarbon age of deposit-feeding molluscs in calcareous environments. Boreas 42, 362–373.
Everest, J.D., Bradwell, T., Stoker, M., Dewey, S., 2013. New age constraints for the maximum extent of the last British–Irish Ice Sheet (NW sector). J. Quat. Sci. 28, 2–7.
Fabel, D., Small, D., Miguens-Rodriguez, M., Freeman, S.P., 2010. Cosmogenic nuclide exposure ages from the 'Parallel Roads' of Glen Roy, Scotland. J. Quat. Sci. 25, 597–603.
Fabel, D., Ballantyne, C.K., Xu, S., 2012. Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British–Irish Ice Sheet in NW Scotland. Quat. Sci. Rev. 55, 91–102.
Fairbanks, R.G., Mortlock, R.A., Chiu, T.-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., Bloom, A.L., 2005. Marine radiocarbon calibration curve spanning 10,000 to 50,000 years B.P. Based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals. Quat. Sci. Rev. 24, 1781–1796.
Flint, R.F., 1955. Rates of advance and retreat of the margin of the late-Wisconsin ice sheet. Am. J. Sci. 253, 249–255.
Frankel, K.L., Finkel, R.C., Owen, L.A., 2010. Terrestrial cosmogenic nuclide geochronology data reporting standards needed. EOS Trans. Am. Geophys. Union 91, 31–32.
Fuchs, M., Owen, L.A., 2008. Luminescence dating of glacial and associated sediments: review, recommendations and future directions. Boreas 37 (4), 636–659.
Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: part I, experimental design and statistical models. Archaeometry 41, 339–364.
Gemmell, A.M.D., 1988a. Thermoluminescence dating of glacially transported sediments: some considerations. Quat. Sci. Rev. 7, 277–285.
Gemmell, A.M.D., 1988b. Zeroing of the TL signal in sediment undergoing fluvioglacial transport. An example from Austerdalen, Western Norway. Quat. Sci. Rev. 7, 339–345.
Glasser, N.F., Harrison, S., Ivy-Ochs, S., Duller, G.A., Kubik, P.W., 2006. Evidence from the Rio Bayo valley on the extent of the North Patagonian Icefield during the Late Pleistocene–Holocene transition. Quat. Res. 65, 70–77.
Godwin, H., Willis, E.H., 1959. Radiocarbon dating of the Late-glacial period in Britain. Proc. R. Soc. Lond. B Biol. Sci. 150, 199–215.
Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quat. Sci. Rev. 20, 1475–1560.
Gosse, J.C., Evenson, E.B., Klein, J., Lawn, B., Middleton, R., 1995. Precise cosmogenic ^{10}Be measurements in western North America: support for a global Younger Dryas cooling event. Geology 23, 877–880.
Graf, K.E., 2009. "The good, the bad, and the ugly": evaluating the radiocarbon chronology of the middle and late Upper Paleolithic in the Enisei River valley, south-central Siberia. J. Archaeol. Sci. 36, 694–707.
Grimm, E.C., Maher, L.J., Nelson, D.M., 2009. The magnitude of error in conventional bulk-sediment radiocarbon dates from central North America. Quat. Res. 72, 301–308.
Hågvar, S., Ohlson, M., 2013. Ancient carbon from a melting glacier gives high ^{14}C age in living pioneer invertebrates. Sci. Rep. 3, 2820.
Hallet, B., 1979. A theoretical model of glacial abrasion. J. Glaciol. 23, 39–50.
Hallet, B., Hunter, L., Bogen, J., 1996. Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. Glob. Planet. Chang. 12, 213–235.
Heier-Nielsen, S., Conradsen, K., Heinemeier, J., Knudsen, K.L., Nielsen, H.L., Rud, N., Sveinbjörnsdóttir, Á.E., 1995. Radiocarbon dating of shells and foraminifera from the Skagen core, Denmark: evidence of reworking. Radiocarbon 37, 119–130.
Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W., 2011. Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. Earth Planet. Sci. Lett. 302, 71–80.
Hughes, A.L., Greenwood, S.L., Clark, C.D., 2011. Dating constraints on the last British-Irish Ice Sheet: a map and database. J. Maps 7, 156–184.
Hughes, A.L., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I., 2016. The last Eurasian ice sheets–a chronological database and time-slice reconstruction, DATED-1. Boreas 45, 1–45.
Ivy-Ochs, S., Schlüchter, C., Kubik, P.W., Denton, G.H., 1999. Moraine exposure dates imply synchronous Younger Dryas glacier advances in the European Alps and in the Southern Alps of New Zealand. Geogr. Annal. Ser. A Phys. Geogr. 81, 313–323.
Jacobi, R.M., Higham, T.F.G., 2008. The "Red Lady" ages gracefully: new ultrafiltration AMS determinations from Paviland. J. Hum. Evol. 55, 898–907.
Jacobi, R.M., Rose, J., MacLeod, A., Higham, T.F., 2009. Revised radiocarbon ages on woolly rhinoceros (Coelodonta antiquitatis) from western central Scotland: significance for timing the extinction of woolly rhinoceros in Britain and the onset of the LGM in central Scotland. Quat. Sci. Rev. 28, 2551–2556.
Kershaw, P.J., 1986. Radiocarbon dating of Irish Sea sediments. Estuar. Coast. Shelf Sci. 23 (3), 295–303.
King, G.E., Robinson, R.A.J., Finch, A.A., 2014. Towards successful OSL sampling strategies in glacial environments: deciphering the influence of depositional processes on bleaching of modern glacial sediments from Jostedalen, Southern Norway. Quat. Sci. Rev. 89, 94–107.
Kirkbride, M.P., Bell, C.M., 2010. Edge-roundness of boulders of Torridonian Sandstone (northwest Scotland): applications for relative dating and implications for warm and cold climate weathering rates. Boreas 39, 187–198.
Kirkbride, M.P., Dugmore, A.J., 2006. Responses of mountain ice caps in central Iceland to Holocene climate change. Quat. Sci. Rev. 25, 1692–1707.
Kirkbride, M.P., Dugmore, A.J., 2008. Two millennia of glacier advances from southern Iceland dated by tephrochronology. Quat. Res. 70, 398–411.
Kitagawa, H., van der Plicht, J., 1998. Atmospheric radiocarbon calibration to 45,000 yr BP: late glacial fluctuations and cosmogenic isotope production. Science 279, 1187–1190.
Lancaster, N., 2008. Desert dune dynamics and development: insights from luminescence dating. Boreas 37, 559–573.
Lepper, K., Fisher, T.G., Hajdas, I., Lowell, T.V., 2007. Ages for the Big Stone Moraine and the oldest beaches of glacial Lake Agassiz: implications for deglaciation chronology. Geology 35, 667–670.
Libby, W.F., Anderson, E.C., Arnold, J.R., 1949. Age determination by radiocarbon content: world-wide assay of natural radiocarbon. Science 109, 227–228.
Lifton, N., Sato, T., Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. Earth Planet. Sci. Lett. 386, 149–160.
Livingstone, S.J., Piotrowski, J.A., Bateman, M.D., Ely, J.C., Clark, C.D., 2015. Discriminating between subglacial and proglacial lake sediments: an example from the Dänischer Wohld Peninsula, northern Germany. Quat. Sci. Rev. 112, 86–108.
Long, A., Kalin, R.M., 1990. A suggested quality assurance protocol for radiocarbon dating laboratories. Radiocarbon 32, 329.
Lowe, D.J., 2011. Tephrochronology and its application: a review. Quat. Geochronol. 6, 107–153.
Lowe, J.J., Walker, M.J.C., 2000. Radiocarbon dating the last glacial-interglacial transition (Ca. 14-9 14C ka BP) in terrestrial and marine records: the need for new quality assurance protocols. Radiocarbon 42, 53–68.
Lowe, J.J., Walker, M., 2015. Measuring Quaternary time: a 50-year perspective. J. Quat. Sci. 30, 104–113.
Lowe, J.J., Hoek, W.Z., I.N.T.I.M.A.T.E., 2001. Inter-regional correlation of palaeoclimatic records for the Last Glacial–Interglacial Transition: a protocol for improved precision recommended by the INTIMATE project group. Quat. Sci. Rev. 20, 1175–1187.
Lowe, J.J., Walker, M.J.C., Scott, E.M., Harkness, D.D., Bryant, C.L., Davies, S.M., 2004. A coherent high-precision radiocarbon chronology for the Late-glacial sequence at Sluggan Bog, Co. Antrim, Northern Ireland. J. Quat. Sci. 19 (2), 147–158.
Lowell, T.V., Fisher, T.G., Hajdas, I., Glover, K., Loope, H., Henry, T., 2009. Radiocarbon deglaciation chronology of the Thunder Bay, Ontario area and implications for ice sheet retreat patterns. Quat. Sci. Rev. 28, 1597–1607.
Lukas, S., Spencer, J.Q., Robinson, R.A., Benn, D.I., 2007. Problems associated with luminescence dating of Late Quaternary glacial sediments in the NW Scottish Highlands. Quat. Geochronol. 2, 243–248.
Mangerud, J., Gulliksen, S., 1975. Apparent radiocarbon ages of recent marine shells from Norway, Spitsbergen, and Arctic Canada. Quat. Res. 5, 263–273.
Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R., Balco, G., 2016a. Cosmogenic nuclide systematics and the CRONUScalc program. Quat. Geochronol. 31, 160–187.
Marrero, S.M., Phillips, F.M., Caffee, M.W., Gosse, J.C., 2016b. CRONUS-Earth cosmogenic ^{36}Cl calibration. Quat. Geochronol. 31, 199–219.
Masarik, J., Reedy, R.C., 1995. Terrestrial cosmogenic-nuclide production systematics calculated from numerical simulations. Earth Planet. Sci. Lett. 136, 381–395.
McCabe, A.M., Clark, P.U., Clark, J., Dunlop, P., 2007. Radiocarbon constraints on readvances of the British–Irish Ice Sheet in the northern Irish Sea Basin during the last deglaciation. Quat. Sci. Rev. 26, 1204–1211.
McCarroll, D., Stone, J.O., Ballantyne, C.K., Scourse, J.D., Fifield, L.K., Evans, D.J., Hiemstra, J.F., 2010. Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream. Quat. Sci. Rev. 29 (15), 1844–1852.
Millard, A.R., 2014. Conventions for reporting radiocarbon determinations. Radiocarbon 56, 555–559.
Moreno, P.I., Kaplan, M.R., Francois, J.P., Villa-Martínez, R., Moy, C.M., Stern, C.R., Kubik, P.W., 2009. Renewed glacial activity during the Antarctic cold reversal and persistence of cold conditions until 11.5 ka in southwestern Patagonia. Geology 37, 375–378.
Murray, A.S., Olley, J.M., 2002. Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. Geochronometria 21, 1–16.
Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiat. Meas. 32, 57–73.
Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., Arnold, J.R., 1989. Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. J. Geophys. Res. Solid Earth 94, 17907–17915.

Nishiizumi, K., Finkel, R.C., Klein, J., Kohl, C.P., 1996. Cosmogenic production of ^{7}Be and ^{10}Be in water targets. J. Geophys. Res. 101, 22225–22232.

Ó'Cofaigh, C., Evans, D.J., 2007. Radiocarbon constraints on the age of the maximum advance of the British–Irish Ice Sheet in the Celtic Sea. Quat. Sci. Rev. 26, 1197–1203.

Ó'Cofaigh, C., Telfer, M.W., Bailey, R.M., Evans, D.J., 2012. Late Pleistocene chronostratigraphy and ice sheet limits, southern Ireland. Quat. Sci. Rev. 44, 160–179.

Olsson, I.U., 1986. A study of errors in ^{14}C dates of peat and sediment. Radiocarbon 28, 429–435.

Osborn, G., Clapperton, C., Davis, P.T., Reasoner, M., Rodbell, D.T., Seltzer, G.O., Zielinski, G., 1995. Potential glacial evidence for the Younger Dryas event in the cordillera of North and South America. Quat. Sci. Rev. 14, 823–832.

Owen, L.A., Finkel, R.C., Caffee, M.W., 2002. A note on the extent of glaciation throughout the Himalaya during the global Last Glacial Maximum. Quat. Sci. Rev. 21, 147–157.

Pawley, S.M., Bailey, R.M., Rose, J., Moorlock, B.S., Hamblin, R.J., Booth, S.J., Lee, J.R., 2008. Age limits on Middle Pleistocene glacial sediments from OSL dating, north Norfolk, UK. Quat. Sci. Rev. 27, 1363–1377.

Peacock, J.D., Graham, D.K., Robinson, J.E., Wilkinson, I., 1977. Evolution and Chronology of Lateglacial Marine Environments at Lochgilphead, Scotland. In: Gray, J.M., Lowe, J.J. (Eds.), Studies in the Scottish Lateglacial Environment. Pergamon Press, Oxford, pp. 89–100.

Peacock, J.D., Graham, D.K., Wilkinson, I.P., 1978. Late-Glacial and post-Glacial marine environments at Ardyne, Scotland, and their significance in the interpretation of the history of the Clyde Sea area. Rep. Inst. Geol. Sci. 78 (17), 1–25.

Penny, L.F., Coope, G.R., Catt, J.A., 1969. Age and insect fauna of the Dimlington silts, East Yorkshire. Nature (London) 224, 65–67.

Pettitt, P.B., Davies, W., Gamble, C.S., Richards, M.B., 2003. Palaeolithic radiocarbon chronology: quantifying our confidence beyond two half-lives. J. Archaeol. Sci. 30, 1685–1693.

Phillips, F.M., Zreda, M.G., Smith, S.S., Elmore, D., Kubik, P.W., Sharma, P., 1990. Cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, eastern Sierra Nevada. Science 248, 1529–1532.

Phillips, F.M., Bowen, D.Q., Elmore, D., 1994. Surface exposure dating of glacial features in Great Britain using cosmogenic chlorine-36: preliminary results. Mineral. Mag. A 58, 722–723.

Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. Quat. Res. 59, 255–261.

Putnam, A.E., Schaefer, J.M., Barrell, D.J.A., Vandergoes, M., Denton, G.H., Kaplan, M.R., Finkel, R.C., Schwartz, R., Goehring, B.M., Kelley, S.E., 2010. In situ cosmogenic 10 Be production-rate calibration from the Southern Alps, New Zealand. Quat. Geochronol. 5, 392–409.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., 2006. A new Greenland ice core chronology for the last glacial termination. J. Geophys. Res. Atmos. 111 (D6).

Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869–1887.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., Scheuchl, B., 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophys. Res. Lett. 41, 3502–3509.

Roberts, H.M., 2008. The development and application of luminescence dating to loess deposits: a perspective on the past, present and future. Boreas 37, 483–507.

Robinson, M., Ballantyne, C.K., 1979. Evidence for a glacial readvance pre-dating the Loch Lomond Advance in Wester Ross. Scott. J. Geol. 15, 271–277.

Rodnight, H., 2008. How many equivalent dose values are needed to obtain a reproducible distribution. Ancient TL 26, 3–10.

Schimmelpfennig, I., Benedetti, L., Finkel, R., Pik, R., Blard, P.H., Bourles, D., Burnard, P., Williams, A., 2009. Sources of in-situ 36 Cl in basaltic rocks. Implications for calibration of production rates. Quat. Geochronol. 4, 441–461.

Scott, E.M., Cook, G., Naysmith, P., 2010. The Fifth International Radiocarbon Intercomparison (VIRI): an assessment of laboratory performance in stage 3. Radiocarbon 53, 859–865.

Scourse, J.D., Haapaniemi, A.I., Colmenero-Hidalgo, E., Peck, V.L., Hall, I.R., Austin, W.E., Knutz, P.C., Zahn, R., 2009. Growth, dynamics and deglaciation of the last British–Irish ice sheet: the deep-sea ice-rafted detritus record. Quat. Sci. Rev. 28, 3066–3084.

Shotton, F.W., 1972. An example of hard-water error in radiocarbon dating of vegetable matter. Nature 240, 460–461.

Small, D., Fabel, D., 2015. A Lateglacial ^{10}Be production rate from glacial lake shorelines in Scotland. J. Quat. Sci. 30, 509–513.

Small, D., Rinterknecht, V., Austin, W.E.N., Fabel, D., Miguens-Rodriguez, M., 2012. In situ cosmogenic exposure ages from the Isle of Skye, northwest Scotland: implications for the timing of deglaciation and readvance from 15 to 11 ka. J. Quat. Sci. 27, 150–158.

Small, D., Austin, W.E.N., Rinterknecht, V., 2013. Freshwater influx, hydrographic reorganization and the dispersal of ice-rafted detritus in the sub-polar North Atlantic Ocean during the last deglaciation. J. Quat. Sci. 28, 527–535.

Small, D., Rinterknecht, V., Austin, W.E.N., Bates, R., Benn, D.I., Scourse, J.D., Bourlès, D.L., Hibbert, F.D., Team, A.S.T.E.R., 2016. Implications of ^{36}Cl exposure ages from Skye, northwest Scotland for the timing of ice stream deglaciation and deglacial ice dynamics. Quat. Sci. Rev. 150, 130–145.

Smedley, R.K., Glasser, N.F., Duller, G.A.T., 2016. Luminescence dating of glacial advances at Lago Buenos Aires (~46° S), Patagonia. Quat. Sci. Rev. 134, 59–73.

Smedley, R.K., Scourse, J.D., Small, D., Hiemstra, J.F., Bateman, M.D., Burke, M.J., Chiverrell, R.C., Clark, C., Davies, S.M., Duller, G.A.T., Fabel, D., Gheorghiu, D.M., McCarroll, D., Xu, S., 2016. New age constraints for the limit of the British-Irish Ice Sheet on the Isles of Scilly. J. Quat. Sci. http://dx.doi.org/10.1002/jqs.2922 (in press).

Stokes, C.R., Tarasov, L., Blomdin, R., Cronin, T.M., Fisher, T.G., Gyllencreutz, R., Hättestrand, C., Heyman, J., Hindmarsh, R.C., Hughes, A.L., Jakobsson, M., 2015. On the reconstruction of palaeo-ice sheets: recent advances and future challenges. Quat. Sci. Rev. 125, 15–49.

Stone, J.O., Ballantyne, C.K., 2006. Dimensions and deglacial chronology of the Outer Hebrides Ice Cap, northwest Scotland: implications of cosmic ray exposure dating. J. Quat. Sci. 21, 75–84.

Stone, J.O., Balco, G.A., Sugden, D.E., Caffee, M.W., Sass, L.C., Cowdery, S.G., Siddoway, C., 2003. Holocene deglaciation of Marie Byrd land, west Antarctica. Science 299, 99–102.

Stroeven, A.P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B.W., Harbor, J.M., Jansen, J.D., Olsen, L., Caffee, M.W., 2015. Deglaciation of Fennoscandia. Quat. Sci. Rev. http://dx.doi.org/10.1016/j.quascirev.2015.09.016.

Stuiver, M., Polach, H.A., 1977. Discussion; reporting of C-14 data. Radiocarbon 19, 355–363.

Stuiver, M., Reimer, P.J., 1986. A computer program for radiocarbon age calibration. Radiocarbon 28, 1022–1030.

Stuiver, M., Reimer, J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Stuiver, M., Suess, H.E., 1966. On the relationship between radiocarbon dates and true sample ages. Radiocarbon 8, 534–540.

Svendsen, J.I., Briner, J.P., Mangerud, J., Young, N.E., 2015. Early break-up of the Norwegian channel ice stream during the last glacial maximum. Quat. Sci. Rev. 107, 231–242.

Swanson, T.W., Caffee, M.L., 2001. Determination of 36 Cl production rates derived from the well-dated deglaciation surfaces of Whidbey and Fidalgo Islands, Washington. Quat. Res. 56, 366–382.

Telford, R.J., Heegaard, E., Birks, H.J.B., 2004. All age–depth models are wrong: but how badly? Quat. Sci. Rev. 23, 1–5.

Thomas, P.J., Murray, A.S., Kjær, K., Funder, S., Larsen, E., 2006. Optically Stimulated Luminescence (OSL) dating of glacial sediments from Arctic Russia-depositional bleaching and methodological aspects. Boreas 35, 587–599.

Thomsen, K.J., Murray, A.S., Bøtter-Jensen, L., Kinahan, J., 2007. Determination of burial dose in incompletely bleached fluvial samples using single grains of quartz. Radiat. Meas. 42, 370–379.

Thomsen, K.J., Murray, A.S., Jain, M., Bøtter-Jensen, L., 2008. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. Radiat. Meas. 43, 1474–1486.

Törnqvist, T.E., de Jong, A.F., Oosterbaan, W.A., Van der Borg, K., 1992. Accurate dating of organic deposits by AMS 14C measurement of macrofossils. Radiocarbon 34, 566–577.

Turney, C.S., Coope, G.R., Harkness, D.D., Lowe, J.J., Walker, M.J., 2000. Implications for the dating of Wisconsinan (Weichselian) Late-Glacial events of systematic radiocarbon age differences between terrestrial plant macrofossils from a site in SW Ireland. Quat. Res. 53, 114–121.

van Asch, N., Lutz, A.F., Duijkers, M.C., Heiri, O., Brooks, S.J., Hoek, W.Z., 2012. Rapid climate change during the Weichselian Lateglacial in Ireland: Chironomid-inferred summer temperatures from Fiddaun, Co. Galway. Palaeogeogr. Palaeoclimatol. Palaeoecol. 315, 1–11.

Waelbroeck, C., Duplessy, J.C., Michel, E., Labeyrie, L., Paillard, D., Duprat, J., 2001. The timing of the last deglaciation in North Atlantic climate records. Nature 412, 724–727.

Walker, M.J.C., Bryant, C., Coope, G.R., Harkness, D.D., Lowe, J.J., Scott, E.M., 2001. Towards a radiocarbon chronology of the Late-Glacial: sample selection strategies. Radiocarbon 43, 1007–1019.

Walker, M.J.C., Coope, G.R., Sheldrick, C., Turney, C.S.M., Lowe, J.J., Blockley, S.P.E., Harkness, D.D., 2003. Devensian Lateglacial environmental changes in Britain: a multi-proxy environmental record from Llanilid, South Wales, UK. Quat. Sci. Rev. 22, 475–520.

Wallinga, J., 2002. On the detection of OSL age overestimation using single-aliquot techniques. Geochronometria 21, 17–26.

Wintle, A.G., 1973. Anomalous fading of Thermo-luminescence in mineral samples. Nature 245, 143–144.

Wintle, A.G., 1997. Luminescence dating: laboratory procedures and protocols. Radiat. Meas. 27, 769–817.

Wohlfarth, B., Blaauw, M., Davies, S.M., Andersson, M., Wastegard, S., Hormes, A., Possnert, G., 2006. Constraining the age of Lateglacial and early Holocene pollen zones and tephra horizons in southern Sweden with Bayesian probability methods. J. Quat. Sci. 21, 321–334.

Young, N.E., Schaefer, J.M., Briner, J.P., Goehring, B.M., 2013. A ^{10}Be production-rate calibration for the Arctic. J. Quat. Sci. 28, 515–526.

Zimmerman, S.G., Evenson, E.B., Gosse, J.C., Erskine, C.P., 1994. Extensive boulder erosion resulting from a range fire on the type-Pinedale moraines, Fremont Lake, Wyoming. Quat. Res. 42, 255–265.

Zreda, M.G., Phillips, F.M., Elmore, D., Kubik, P.W., Sharma, P., Dorn, R.I., 1991. Cosmogenic chlorine-36 production rates in terrestrial rocks. Earth Planet. Sci. Lett. 105, 94–109.